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Seismic Evaluation of Auburn Damsite. Volume 4
Analysis of Faulting in the Auburn Damsite

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16. ABSTRACT The report presents additional data and interpretations assembled by various consultants since publication of the Project Geology Report. A structural analysis of F-1 based on overall geometry and observed slicken-sides is presented and are used to estimate potential directions and magnitudes of net slip along the F-1 fault zone. Included as an appendix is a study by consultant Robert Compton titled "Gouge and Associated Deformation Along Fault F-1, Auburn Damsite." Some of the conclusions reached are: (1) Maximum net slip of a shear termed the Steeply Dipping shear is 13.4 feet. (2) Displacement of the Steeply Dipping shear is the sum of episodic movements. (3) Post Steeply Dipping shear movement along F-1 has a magnitude of between 2 and 12 feet. (4) Based on observed relationships, F-1 may have moved last about 120 million years before present. (5) Displacement on foliation structures producing similar styles of deformation due to different stresses separated by 110 million years. Six appended drawings and 5 included in the text which are color printed and/or oversize as well as 10 color xerox prints are not included in the report because they could not be microfilmed. These drawings are available from the U.S. Bureau of Reclamation, Denver.		
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**ANALYSIS OF FAULTING
IN THE AUBURN DAMSITE**

by

U.S. BUREAU OF RECLAMATION

AUBURN, CALIFORNIA

ANALYSIS OF FAULTING
IN THE AUBURN DAMSITE

By

Dean Ostenaa and Richard H. Throner

Under Supervision of Louis R. Frei
Project Geologist

U.S. Bureau of Reclamation
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Research Center, Building #67, Denver, CO
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I. PREFACE

This report is one of several supplements to the U.S. Bureau of Reclamation Project Geology Report (Frei, et al., 1977) on the seismic evaluation of Auburn damsite and was prepared by members of the USBR Auburn Project geology staff. Consultants for the USBR have prepared other supplemental reports on fault and dike relationships; gouge in the F-1 fault zone; the Maidu East shear zone; and a literature search of published geologic data pertaining to the western Sierran foothills. A complete listing of these reports by author is included in the reference section. This report, together with those of the consultants, presents additional data and interpretations assembled since publication of the Project Geology Report.

From the beginning of the seismic evaluation studies the Steeply Dipping shear was known as the only shear which offset the F-1 fault zone, thus forming a time line relative to the last movement of F-1. However, no definitive information on the age of the Steeply Dipping shear and hence its last movement was developed prior to this study. The lack of definitive evidence regarding the last increment of movement on F-1 which came forth from the dike/fault study (McMillan and O'Brient, 1977) spurred additional efforts to resolve the age of the Steeply Dipping shear. These efforts consisted of additional mapping along the Steeply Dipping shear, a detailed analysis of features it offsets, and a review of evidence indicating the nature of last movement on F-1. In addition, structural relationships along other structures in the damsite subparallel to the Steeply Dipping shear were reviewed.

The principal objectives of this report are threefold:

1. Detail the relationships along the Steeply Dipping shear which would indicate its age and displacement;

2. Summarize the pertinent structural information regarding the nature and timing of last movement on F-1; and
3. Place both the Steeply Dipping shear and F-1 in a structural framework with respect to other structures at the Auburn damsite.

A structural analysis of F-1, based on its overall geometry and observed slickensides, is presented in Appendix A. These data are used to estimate potential magnitudes and directions of post-Steeply Dipping shear net slip on F-1.

Appendix B presents an analysis of the accuracy of net slip solutions for the Steeply Dipping shear.

Appendix C is a brief, but detailed, report by Professor Robert R. Compton titled "Gouge and Associated Deformation Along Fault F1, Auburn Damsite." In this report Dr. Compton describes the results of petrographic studies he performed on polymerized samples obtained from F-1 shear zone in the lower left abutment of the Auburn Dam foundation.

Lastly, a packet in the back of this report contains all drawings referenced in this report and the appendixes. These drawings include geologic plan maps illustrating the overall relationships in the lower left abutment of the dam foundation and service spillway areas, as well as more detailed relationships in specific areas. Also included are determinations of net slip on pertinent structures. Drawings in the packet are referred to in the text by an index number located in the lower right-hand corner below the title block rather than their USBR drawing number. On all drawings and figures in this report, the Steeply Dipping shear is labeled "SDS" and mapped traces are shown in green. Drawing No. 1 is an "Explanation of Geologic Symbols and Units."

II. SUMMARY OF CONCLUSIONS

1. The maximum net slip of the Steeply Dipping shear is 13.4 feet. Displacements are down to the east and dip slip with a small right-lateral component. Computed slip directions agree with slickensides observed along the Steeply Dipping shear.
2. The total displacement along the Steeply Dipping shear is the sum of several episodic movements, and not the result of a single event. Smaller net slips computed using successively younger offset features indicate that the Steeply Dipping shear was active prior to and during periods of mineralization more than about 120 million years ago.
3. The youngest features offset by the Steeply Dipping shear are various aged mineralized veinlets of quartz, calcite, and epidote. Post-youngest veinlet net slip on the Steeply Dipping shear is between 2 and 4 feet.
4. Post-Steeply Dipping shear displacement is expressed by two, and possibly three faults: F-1 exhibits 2 to 3 feet of left-lateral separation of the Steeply Dipping shear; the Cutslope shear exhibits 4 feet of left-lateral separation of the Steeply Dipping shear; and F-25 offsets all possible projections of the Steeply Dipping shear up to 25 feet.
5. A comparison of the lateral separations by F-1 of the Steeply Dipping shear versus those of lithologic units in the left abutment indicates that the separation of the Steeply Dipping shear represents about 2 percent of the total lateral separation on F-1. Similar comparisons for the Cutslope shear and F-25 indicate that 100 percent of the lateral separations by the Cutslope shear and possibly F-25 are post-Steeply Dipping

shear in age. Thus, these two structures apparently formed after all movement on the Steeply Dipping Shear.

6. The offset of the Steeply Dipping shear by F-1, the Cutslope shear, and possibly F-25, indicates that the last movement on the Steeply Dipping shear occurred at a time when F-zone type structures were being formed and experiencing repeated movements. Because the Cutslope shear contains mineralization similar to other F-zones, it is older than about 120 million years. Therefore, the last movement on the Steeply Dipping shear occurred prior to about 120 million years ago. The comparable lateral separations of the Steeply Dipping shear by F-1 and the Cutslope shear suggests that these offsets may be related in time. The Cutslope shear formed and first offset the Steeply Dipping shear more than about 120 million years ago and it seems reasonable that F-1 may have moved at that time also.

7. Neither the magnitude, direction, nor absolute time of the last movement on F-1 which offset the Steeply Dipping shear can be stated categorically. However, the left-lateral separation of the Steeply Dipping shear combined with the possible directions of slip on F-1 indicated by slickensides suggests that the last movement on F-1 had a reverse component. The magnitude of possible net slips for this last F-1 movement is between 2 and 12 feet.

8. Dominantly dip-slip displacement has occurred on some T-zones and foliation structures subparallel to the Steeply Dipping shear throughout the Auburn damsite. Relationships of some of these structures to F-zones

indicate that alternating, repeated movements have occurred on both sets of structures. Relationships of foliation shears in the left abutment to mineralized F-zones suggests movement occurred more than 120 million years ago. These movements most likely resulted from east-west to northeast-southwest compression.

9. Similar styles of deformation along the Steeply Dipping shear and the Maidu East shear zone reflect deformation resulting from different stress environments separated by more than 110 million years.

III. STRUCTURAL RELATIONSHIPS ALONG THE STEEPLY DIPPING SHEAR

Introduction

The Steeply Dipping shear intersects F-1 near axis station 33+00 in the left abutment foundation excavation. It is the only shear known to offset F-1. Younger movement on F-1 offset the Steeply Dipping shear as shown by its 2- to 3-foot left-lateral separation of the Steeply Dipping shear. This separation is about 2 percent of the maximum observed left-lateral separation along F-1 in the left abutment. Thus, the Steeply Dipping shear represents a time line relative to the last movement on F-1.

The significance of the relationship between F-1 and the Steeply Dipping shear was recognized early in the seismic studies at Auburn damsite. The intersection of F-1 and the Steeply Dipping shear was excavated in five stages and data from the first three stages were included in the Bureau of Reclamation's Project Geology Report on the seismic evaluation of Auburn damsite (Frei, et al., 1977).

Studies of the Steeply Dipping shear were concentrated in three general locations: (1) at and adjacent to its intersection with F-1, (2) along its strike in the left abutment foundation excavation, and (3) in the service spillway excavation, where projections of the Steeply Dipping shear would intersect F-25. The general locations of these areas can be seen on the 1-inch = 50-foot scale geologic plan, drawing No. 2.

In the foundation excavation numerous features intersect and are offset by the Steeply Dipping shear. Varied lateral separations of subparallel features offset by the Steeply Dipping shear suggest they may be of different

ages, with movement occurring on the Steeply Dipping shear between the formation of each. Net slip solutions, which use offset features of similar age, provide the most reliable indication of displacement magnitude and direction post these features. In contrast, net slip solutions which utilize offset features of different ages may yield misleading estimates of net slip magnitude and direction owing to the possibility of movement occurring between the formation of the offset features.

Four groups of features offset by the Steeply Dipping shear have been identified in the foundation excavation. Each group is limited to features of similar apparent age. In order of decreasing age these are: (1) offset elements of F-1, (2) latite dikes, (3) quartz-calcite healed shears, and (4) mineralized veinlets. Most of these features dip moderately to the southwest and have similar rakes on the Steeply Dipping shear. Thus, net slips cannot be computed directly for some age groups. In these cases a net slip direction is assumed based on directions indicated by other age groups and slickensides observed along the Steeply Dipping shear.

Younger movement offsetting the Steeply Dipping shear occurs along two and possibly three F-zone type shears. These are F-1, the Cutslope shear, and F-25 (see drawing No. 2). These three structures define a time line which limits the age of youngest movement on the Steeply Dipping Shear.

Slickensides on the Steeply Dipping Shear

Locations of observed slickensides on the Steeply Dipping shear are shown on the geologic plans on drawing No. 3, and are plotted on an equal area projection (figure 4-A on drawing No. 4). The average attitude of the Steeply Dipping shear is N. 5° E., 76° SE., and most observed slickensides plot on or adjacent to this average plane with rakes of 75° to 90° to the south. These data indicate the direction of movement on the Steeply Dipping shear as primarily dip slip with a small lateral component.

Computation of Steeply Dipping Shear Net Slips

In cases where all features of a similar age group are subparallel, where a net slip direction cannot be reliably computed, a slip direction with a rake of 70° to the south has been assumed. This is an extremely conservative assumption based on slickensides and net slip solutions using other offset features. Slickensides with rakes nearest 70° to the south are more critical to the solutions, because most features offset by the Steeply Dipping shear also have rakes to the south. Thus, it is theoretically possible that the net slip direction could be parallel to the intersection of these offset features and the Steeply Dipping shear. However, analyses of measured attitudes and slickensides indicate that the southwest dipping features offset by the Steeply Dipping shear have maximum rakes ranging from 41° to 57°, whereas slickensides and computed net slip directions have minimum rakes of 70° (figures 4-A through 4-I on drawing No. 4).

To select attitudes of offset features for computing net slips, all measured strikes and dips were tabulated and values giving the steepest credible

rakes on the Steeply Dipping shear were used. In some cases, one or two attitudes giving slightly higher rakes on the Steeply Dipping shear were considered not representative of the offset feature and were not used in the analyses. The value of 70° for the lower boundary of the slickenside data is based on the rotation of these data through the range of observed orientations for the Steeply Dipping shear. Because maximum and minimum values were used for opposing orientation parameters in the analyses (rake of offset feature versus rake of slip direction), the values used are those closest to being "along the plunge" of the intersection of these features with the Steeply Dipping shear. Increases in the rake of the slip direction, or decreases in rake of the offset features, reduce the absolute values of net slip and make them less sensitive to small changes in the angles used, but do not change the net slip of different features relative to one another. Lateral separations used in net slip computations were measured in the field and are the maximum values observed at all stages of excavation. A discussion of the accuracy of net slip computations for both assumed slip directions and two offset features is given in Appendix B.

Group 1 - Relationship of the Steeply Dipping Shear to Offset Elements of F-1

Offsets by the Steeply Dipping shear of three subparallel elements of F-1 are compared: (1) a csC drag aureole on the footwall of F-1, (2) a latite dike intruded along F-1, and (3) a 1-foot-thick quartz vein along F-1. The aureole and dike both have left-lateral separations of about 8 feet; the quartz vein a maximum of 6 feet. The three elements vary slightly in orientation, striking N. 50° W. to N. 61° W. and dipping 45° to 55°

southwest. Despite these variations, rakes on the Steeply Dipping shear are nearly identical and range from 41° to 45° to the south (see drawing No. 4, figure 4-B).

As a further check on the orientation of the F-1 and Steeply Dipping shear intersection, survey coordinate and elevation data for all five stages of excavation, plus the original invert location, were tabulated. The elevation difference between points at the original invert and those at stage V is about 25 feet. Structurally identical points at all stages were identified and assigned three-dimensional coordinates, then the vector between all possible pairs of correlative points computed. Averaging all of these data, the intersection of F-1 has a rake of 39° to the south on the Steeply Dipping shear. Averaging only stages II through V, the rake of F-1 on the Steeply Dipping shear is 34° , and has a more southerly bearing. On drawing No. 5 these relationships are tabulated and the structurally identical point chosen at each stage is shown on 1-inch = 5-foot scale maps of the intersection area. Pertinent intersection data and the method of computation are also shown.

Net slips for each element of F-1 are computed using the maximum rake derived from field measurements of attitudes of each element (45°), and the rakes of the intersection derived from survey data (39° and 34°). Because all offset elements are subparallel, a net slip direction with a rake of 70° to the south is assumed. With these rakes, and the measured lateral separations, net slip of the dike and csC aureole ranges from 7.6 to 13.4 feet and that of the quartz vein from 5.7 to 8.1 feet. The most reasonable estimate for net slip of the F-1 dike and csC aureole appears to

be 10 to 11 feet. Net slip of the offset F-1 quartz vein is complicated by post-Steeply Dipping shear movement of F-1 along the hanging wall of the quartz vein east of the Steeply Dipping shear and along both the hanging wall and footwall sides of the vein to the west (see 1-inch = 2-foot scale geologic plan on drawing No. 3). This younger F-1 movement may have increased, decreased, or not affected the lateral separation of the quartz vein. It is also possible this quartz vein was emplaced along F-1 after some displacement had occurred along the Steeply Dipping shear. The 6-foot separation used for computing net slip was the largest separation observed. At most stages, the separation of the quartz vein was 4 to 5 feet. If the true lateral separation of the vein is 4 feet, then the post-F-1 quartz vein net slip on the Steeply Dipping shear could be as low as 4 feet. However, the most reasonable estimate of post-quartz vein net slip appears to be about 6 feet. Orthographic solutions for these net slips are shown on figure 4-F on drawing No. 4. Increasing the rake of the slip direction to 90° reduces the magnitudes of these offsets by 28 to 40 percent.

Conclusion. - Net slip on the Steeply Dipping shear shown by offsets of the F-1 dike and csC aureole is most likely about 10 feet. The smaller net slip derived from the F-1 quartz vein results either from a reduction in the apparent separation of the quartz vein due to later movement on F-1 or from emplacement of the quartz vein after the dike and csC aureole had been offset about 3 feet.

Group 2 - Relationship of the Steeply Dipping Shear to Latite Dikes

Four low to moderately dipping latite dikes intersect the Steeply Dipping shear in the current foundation excavation. Three of these dikes dip to

the southwest, the fourth to the northeast. All are cut by the Steeply Dipping shear with vertical and lateral separations ranging from 7 to 9 and 5 to 24 feet, respectively. These separations are all consistent with down-to-the-east displacement on the Steeply Dipping shear. The relationships of these dikes to the Steeply Dipping shear are shown on the 1-inch = 10-foot scale geologic plan on drawing No. 3 and the 1-inch = 50-foot scale geologic plan on drawing No. 2. In addition, the three southwest-dipping dikes were mapped on the original invert surface at 1-inch = 10-foot scale (see figure III-1). Dike separations mapped on the original invert differ markedly from those observed at the current stage; thus, estimates of true fault separation on these dikes are uncertain. Attitudes shown on maps at both stages indicate that orientations of these dikes are extremely variable. For example, on a given dike, strikes may vary by up to 60° and dips by as much as 20° .

The wide variation in measured separations of the latite dikes, together with their relationships to the Steeply Dipping shear, suggests that these dikes may have intruded an already existing shear (see figure III-1). If so, the origin of the Steeply Dipping shear is pre-dike. It is also possible that the irregularities in the dike geometries resulted from differences in the mechanical properties of the country rock (McMillan and O'Brient, 1977) present prior to the formation of the Steeply Dipping shear. Specifically, the amphibolite adjacent to the Steeply Dipping shear has more closely spaced and chloritic cleavage than "typical" amphibolite, and may have sufficiently different mechanical properties to cause the dikes to assume irregular geometries.

Due to the large variations in orientation and separation of individual dikes, no net slip computation based solely on latite dikes is included in this report. However, because the upstream dike dips northeast and provides a check against assumed displacement directions of southwest-dipping features, net slips were computed for the upstream dike with the F-1 dike, F-29, and the Vertical shear. The rake of the upstream dike on the Steeply Dipping shear is shown on figure 4-D on drawing No. 4, and computations of net slip on figure 4-G. Net slips range between 7.4 and 8.8 feet with rakes on the Steeply Dipping shear of 71° to 85° to the south. Although these solutions utilize features of different apparent ages, they do provide a check on possible net slip directions because the upstream dike has a radically different orientation (northeast dip) compared to other features offset by the Steeply Dipping shear.

Conclusion. - Due to the large variations in the orientations and separations of the latite dikes across the Steeply Dipping shear, no net slip computation utilizing only the latite dikes is included. Conclusions regarding displacement by the Steeply Dipping shear are limited to the observation that all apparent vertical and lateral separations are consistent with down-to-the-east displacement. The magnitude of this displacement is probably at least 6 to 8 feet. Although equivocal, field relationships suggest the possibility that latite dikes intruded a pre-existing Steeply Dipping shear.

The northeast-dipping upstream dike provides an opportunity to check net slip directions and magnitudes computed from southwest-dipping structures. Net slip directions and magnitudes computed using the upstream dike with

the F-1 dike, F-29, and the Vertical shear are consistent with other computations and indicate that displacement on the Steeply Dipping shear is mostly dip slip.

Group 3 - Relationship of the Steeply Dipping Shear to Quartz-Healed Shears

Numerous quartz-healed shears and fractures intersect and are offset by the Steeply Dipping shear in the foundation excavation. Of these, three were correlated across the Steeply Dipping shear and used to compute net slip on the Steeply Dipping shear. Two of these shears are designated F-zones (F-29 and F-35) and dip moderately to the southwest; the third, designated the Vertical shear is nearly vertical and strikes about east-west. None of these features offset foliation more than a few-tenths-of-a-foot in the vicinity of the Steeply Dipping shear. F-35 and the Vertical shear die out a short distance east of the Steeply Dipping shear; F-29 is discontinuous to the west and dies out before reaching T-6b. The relationships of these structures are shown on both drawings No. 2 and 3.

Measured lateral separations by the Steeply Dipping shear are 3.5 feet left laterally on F-29; 5.6 feet left laterally on F-35; and 2.1 feet right laterally on the Vertical shear. Net slips can be computed for this group of features because the orientation of the Vertical shear is sufficiently different from that of F-29 and F-35. Figures 4-D and 4-H on drawing No. 4 show the stereographic determination of rakes and net slip solutions for these features. Net slip computed using the Vertical shear and F-35 is 6.8 feet, and with the Vertical shear and F-29, 6.5 feet. These solutions have respective rakes of 76° and 75° to the south and indicate down-to-the-east displacement.

Two other moderately southwest-dipping shears, F-15 and an unnamed subparallel shear, intersect the Steeply Dipping shear on the downstream cutslope of the foundation excavation. Between elevations 710 and 720, F-15 intersects both T-6b and the Steeply Dipping shear. The left-lateral separations of the Steeply Dipping shear and T-6b by F-15 are about 3 and 4 feet, respectively. Younger movement on both the Steeply Dipping shear and T-6b offset F-15 and shows a total of about 4 feet of down-to-the-east vertical separation.

Between elevations 730 and 735 the unnamed shear subparallel to F-15 intersects the Steeply Dipping shear. This shear originally offset the Steeply Dipping shear and T-6b a few-tenths-of-a-foot left laterally. Younger movement on both the Steeply Dipping shear and T-6b offsets this shear with a cumulative down-to-the-east vertical separation of about 4 feet. About 80 percent of this separation occurs along T-6b.

Conclusion. - The varied orientation of the Vertical shear relative to F-29 and F-35 allows the precise determination of both net slip magnitude and direction. Net slip on the Steeply Dipping shear, post-quartz-healed shears, is about 6.6 feet down-to-the-east with a rake of 75° to the south. Apparent vertical separations of F-15 and the unnamed subparallel shear suggest similar or slightly smaller displacements. However, net slips were not computed using these features because of the difficulties in obtaining reliable attitudes in close proximity to the wire mesh covering the downstream cutslope.

Group 4 - Relationship of the Steeply Dipping Shear to Mineralized Veinlets

On the hanging wall of F-1, the Steeply Dipping shear intersects and offsets several mineralized veinlets. The spatial relationships of these features are shown on both the 1-inch = 2-foot scale and 1-inch = 10-foot scale geologic plan maps on drawing No. 3. These veinlets dip moderately to the south, but have widely divergent strikes. Their rakes on the Steeply Dipping shear are similar and range between 42° and 57° to the south (see figure 4-E on drawing No. 4). Because the rakes are similar, no net slip direction can be derived from these data alone.

To compute the post-veinlet net slip on the Steeply Dipping shear a slip direction with a rake of 70° to the south was assumed. This slip direction is based on net slip directions derived using other offset features, and on slickensides observed along the Steeply Dipping shear. Slickensides on quartz veinlet No. 1, where it is cut by the Steeply Dipping shear, have a rake of about 75° to the south on the Steeply Dipping shear (see 1-inch = 2-foot scale geologic plan on drawing No. 3). Using an assumed slip direction with a 70° rake, and the measured lateral separations, post-veinlet net slips range from 2.6 feet to 6.7 feet. Orthographic solutions for net slip are shown on figure 4-I on drawing No. 4 and the lateral separations and resultant net slip for each veinlet are summarized in table III-1 below:

Table III-1. Summary of net slip for mineralized veinlets

Offset feature	Lateral separation (feet)	Net slip (feet)
Quartz veinlet No. 1	1.2	3.3
Quartz veinlet No. 2	1.8	6.7
Epidote veinlet	3.1	5.2
Calcite veinlet	1.8	2.6

Using a 90° rake for the slip direction reduces the magnitudes of these slips by 35 to 61 percent but does not change the relative order of offset between veinlets. The differences in net slip magnitude for each of the veinlets suggest that they may have different relative ages. These differences possibly resulted from slip on the Steeply Dipping shear between emplacement of each of the veinlets.

The net slips computed for the calcite and epidote veinlets and quartz veinlet No. 2 may not represent the cumulative slip post these veinlets since they do not cross all the branches of the Steeply Dipping shear. However, these veinlets provide limits on slip for each branch of the Steeply Dipping shear. Quartz veinlet No. 1 is considered to be the youngest veinlet which crosses all branches of the Steeply Dipping shear. Thus, maximum post-youngest veinlet net slip on the Steeply Dipping shear is 3.3 feet.

Conclusion. - Quartz veinlet No. 1, apparently the youngest veinlet, can be correlated across the Steeply Dipping shear, with a maximum net slip of 3.3 feet. The assumed slip direction is confirmed by slickensides on quartz veinlet No. 1 where it is offset by the Steeply Dipping shear. The different net slip magnitudes recorded by each of the veinlets suggest that movement occurred on the Steeply Dipping shear between episodes of mineralization.

Relationship of the Steeply Dipping Shear to T-6b

Observed offsets along the Steeply Dipping shear on the downstream cutslope of the foundation excavation indicate that displacement along its main traces diminishes towards the top of the cutslope and increases along T-6b. Thus, on the downstream cutslope, displacement is apparently transferring to the T-6b zone from the Steeply Dipping shear. In the foundation, displacements along T-6b are minor and die out before reaching F-1. F-35 originally displaced T-6b about 4 feet left laterally, but younger movement on T-6b cut F-35 as shown by a down-to-the-east vertical separation of 0.1 to 0.2 foot. Near its intersection with F-1, the T-6b zone becomes smaller and no shears were observed to cut any portion of F-1 or its associated drag aureole (see drawing No. 2).

Relationships of the Steeply Dipping Shear to Younger Structures

The Steeply Dipping shear has been delineated in the foundation excavation by offsets of intersecting features. Within this area two structures, F-1 and the Cutslope shear, offset the trace of youngest displacement on the Steeply Dipping shear. In addition, all possible projections of the

Steeply Dipping shear are offset by F-25 in the service spillway excavation, about 650 feet south of F-1. These three structures strike either normal to or at a high angle to the Steeply Dipping shear and dip moderately to steeply southwest (see drawings No. 2 and 3).

F-1 intersects the Steeply Dipping shear on the upstream side of the foundation excavation. The Steeply Dipping shear originally displaced F-1, but younger movement on F-1 postdates all movement on the Steeply Dipping shear. This last F-1 movement shows 2 to 3 feet of left-lateral separation of the Steeply Dipping shear. This separation is about 2 percent of the maximum observed lateral separation on F-1. The relationships at the F-1 and Steeply Dipping shear intersection do not indicate the youngest possible age for the F-1 movement. As discussed in Appendix A, the left-lateral separation of the Steeply Dipping shear and slickenside directions on F-1 suggest this movement was reverse with a magnitude of about 2 to 12 feet.

The Cutslope shear intersects both the Steeply Dipping shear and T-6b between elevations 745 and 760 on the downstream cutslope of the foundation excavation. This intersection is about 220 feet south of F-1 and only 10 to 15 feet from the unnamed shear subparallel to F-15 which is offset by the Steeply Dipping shear. As illustrated on drawing No. 3, the Cutslope shear offsets all traces of both the Steeply Dipping shear and T-6b about 4 feet left laterally. There is no evidence that the Cutslope shear was ever offset by either the Steeply Dipping shear or T-6b. This suggests that the Cutslope shear formed after last movement on the Steeply Dipping shear. The age of the Cutslope shear is not uniquely defined, but it is mineralized similarly to other F-zones at the Auburn damsite suggesting it

existed prior to the youngest mineralization, or more than about 120 million years ago (Behrman and Meyer, 1977).

F-25 crosses the service spillway about 650 feet south of F-1. It clearly offsets all intersecting structures and shows about 20 feet left-lateral separations of lithologic units (drawing No. 2). Vertical separation of the F-3 dike by F-25 is probably less than 5 feet, but is difficult to assess due to intrusive relationships. These separations suggest that movement on F-25 was dominantly left lateral with a minor reverse component. Abundant mineralization along F-25 indicates that it existed prior to about 120 million years ago.

Offset crosscutting features useful to delineate the Steeply Dipping shear are not present in the service spillway excavation. Thus, the trace of the Steeply Dipping shear cannot be positively identified. Therefore, all zones of shearing in the service spillway excavation with orientations and appearances generally similar to the Steeply Dipping shear were considered potential branches and traced to their intersection with F-25. These shears occur up to 75 feet on either side of T-6 in the service spillway excavation. No shears were observed to cut any branch of F-25.

Because the Steeply Dipping shear cannot be clearly identified in the service spillway excavation, two possibilities must be considered. First, F-25 offsets the Steeply Dipping shear. If so, then F-25 postdates all movement on the Steeply Dipping shear and T-6 because no shears were observed to cut F-25. Alternatively, displacement on the Steeply Dipping shear died

out between the Cutslope shear and F-25. In the latter case, the relative ages of F-25 and the Steeply Dipping shear cannot be determined from relationships in the service spillway excavation.

Conclusion. - The Steeply Dipping shear is offset by at least two and possibly three younger structures. One structure, F-1, shows 2 to 3 feet of left-lateral separation; a second, the Cutslope shear, shows about 4 feet of left-lateral separation; and if the Steeply Dipping shear extends to the third, F-25, the left-lateral separation is about 20 feet.

The exact age of these offsets is not known; however, relationships indicate that the Cutslope shear formed and was mineralized after youngest movement on the Steeply Dipping shear. Thus, movement on the Steeply Dipping shear occurred prior to about 120 million years ago. Movement on the Cutslope shear may have occurred prior to the youngest mineralization or possibly post-mineralization. Similarly, abundant mineralization indicates that F-25 existed pre-mineralization; however, post-mineralization movements cannot be ruled out.

The oldest age for the post-Steeply Dipping shear movement on F-1 is about 120 million years ago as indicated by the relationship of the Steeply Dipping shear to the Cutslope shear. The F-1 and Steeply Dipping shear intersection alone provides no conclusive evidence to limit the magnitude or the youngest possible age of the last F-1 movement. However, the 2 to 3 feet of left-lateral separation of the Steeply Dipping shear by F-1, coupled with the directions of slip on F-1 suggested by slickensides, indicates that the youngest movement(s) on F-1 were reverse with a magnitude between 2 and 12 feet.

Overall Conclusions - Structural Relationships along the Steeply Dipping Shear

The numerous features which intersect the Steeply Dipping shear allow determination of both net slip magnitude and direction on the Steeply Dipping shear as well as identification of the time period when this movement occurred. Net slip on the Steeply Dipping shear of the oldest offset structure, F-1, is about 10 feet. The net slip by the Steeply Dipping shear of the youngest offset feature, quartz veinlet No. 1, is a maximum of 3.3 feet. The relationships of intermediate age features demonstrate that movement occurred on the Steeply Dipping shear between the emplacement or formation of each. The wide range of lateral separations of features with similar rakes on the Steeply Dipping shear suggests, in itself, that movement on the Steeply Dipping shear occurred between their formations. All net slips on the Steeply Dipping shear indicate down-to-the-east displacement, either purely dip slip or with a steep rake to the south.

At least two structures offset the Steeply Dipping shear and are therefore younger features. F-1 and the Cutslope shear both displace the Steeply Dipping shear left laterally; F-1 about 2 to 3 feet, and the Cutslope shear about 4 feet. The post-Steeply Dipping shear net slip on F-1 and the Cutslope shear are not known absolutely. However, the sense of separation of the Steeply Dipping shear by F-1 is consistent with that of older offset structures (e.g., biotite porphyry dike) and suggests continued reverse-oblique slip. Separation by the Cutslope shear is also left lateral and relationships indicate that it formed after last movement on the Steeply Dipping shear. Mineralization similar to that along other F-zones within and along the Cutslope shear indicates a minimum age for this feature of

about 120 million years. Thus, this defines the minimum age for movement on the Steeply Dipping shear, and the maximum age for last movement on both F-1 and the Cutslope shear. The minimum age for movement on both F-1 and the Cutslope shear is not defined.

IV. RELATIONSHIP OF THE STEEPLY DIPPING SHEAR TO T-ZONES AND FOLIATION SHEARS

Introduction

The relationship of the Steeply Dipping shear to F-zones and related structures discussed in Section III indicates that recurrent alternating displacements occurred on diversely oriented structures. Either the same or pulsating stresses produced essentially concurrent Mesozoic deformations on west-northwest striking, moderately southwest dipping F-zones and north-northwest striking, steeply northeast dipping shears and T-zones. The sense of displacement along the Steeply Dipping shear is not unique among structures at the Auburn damsite. Many other shears trending north-northwest, parallel or subparallel to the regional foliation, exhibit a similar sense of displacement.

Examples of Apparent Dip-slip Displacement on Foliation Shears in the Auburn Damsite

Offsets along foliation shears indicate that displacements similar to those on the Steeply Dipping shear have occurred on several other subparallel structures within the Auburn damsite. These observations are tabulated below and their locations shown by number on figure VI-1.

1. Steeply Dipping shear. - Displacement on this shear is down-to-the-east and dip slip with a small right-lateral component. Maximum net slip is estimated to be 10 to 14 feet; all of which occurred prior to about 120 million years ago. As discussed in Section III, F-1 existed prior to

the Steeply Dipping shear; other F-zones formed and moved midway through the period of displacement on the Steeply Dipping shear; and F-1, the Cutslope shear and possibly F-25 either formed or had movement after last movement on the Steeply Dipping shear.

2. T-7. - In the lower left abutment foundation excavation, on the foot-wall of F-1, T-7 and an associated shear intersect F-4. F-4 dips moderately to the southwest and originally offset T-7 a few feet left laterally, consistent with reverse-oblique slip on a F-zone. Younger movement on a shear associated with T-7, offsets F-4 with 1 foot of left-lateral separation. This separation and small, subhorizontal folds and crenulations within the T-zone shear suggests that displacement was down-to-the-east and mostly dip slip. This sense of displacement is further verified by a low-angle latite dike cut by T-7 some 20 to 30 feet north from F-4. Vertical separation of the dike is about 1 foot and consistent with assumed down-to-the-east dip-slip displacement along T-7. Still younger movement on F-4 offset this shear with about 0.5 foot of left-lateral separation. It is also possible, although not conclusive, that even younger movement on the T-zone shear shows about 0.1 foot of left-lateral separation of the youngest F-4 shear plane. The time of these displacements is not clear. Mineralization along F-4 is extensive, but the relationship of the mineralization to the fault movements is uncertain. Both F-4 and T-7 intersect F-1. F-4 either merges with or branches off F-1; T-7 and associated shears all exhibit pronounced left-lateral drag by F-1 and do not appear to cut any portion of F-1.

3. T-7. - In the lower left abutment excavation, on the hanging wall side of F-1, T-7 intersects F-35. F-35 dips moderately to the southwest and originally offset T-7 producing about 3 feet of left-lateral separation consistent with reverse-oblique slip on a F-zone. Subsequent movement on a shear within T-7 offset F-35 and shows about 2 feet of left-lateral separation. This left-lateral separation of F-35 suggests down-to-the-east displacement on T-7. The age of this displacement by T-7 is uncertain. Tracing the T-zone to F-1 shows that neither T-7 nor shears associated with it cut any portion of F-1 including its drag aureole and a dike parallel to F-1.

4. Tunnel No. 3 shears. - Numerous small shears occur within and along the borders of a small metasediment unit in the lower left abutment on the footwall of F-1. In exploratory tunnel No. 3, these shears show 3 to 4 feet of cumulative, down-to-the-east vertical separation of a dike (see figures IV-2 and IV-3). Maps of the original invert excavation, show shears within this same metasediment unit which cut several dikes whose contacts are essentially parallel to the excavation surface. Due to the orientation of these dikes relative to the exposure, lateral separations are not clear, but some suggest down-to-the-east displacement. Tracing these shears to F-1, they are dragged very strongly and do not cut any portion of F-1.

Correlation of a metasediment unit of similar thickness and appearance on the hanging wall of F-1 suggests a total of 100 to 120 feet of left-lateral separation on F-1 in this area. Because of poor exposure, the relationships

of the shears in the hanging wall metasediment are not clear; however, no shears associated with it cut the F-1 drag aureole or any related structures.

Summary. - Example 1, the Steeply Dipping shear, is both post-latite dike and younger than movement on some F-zones. It cuts F-1, but is post-dated by last movement on F-1. Examples 2, 3, and 4 are post-latite dike and two have displacements known to be younger than those on some F-zones. In addition, the F-4 and T-7 relationship indicates a history of alternating movement on the two structures, although which one moved last is not clear. The observed offsets occur within about 100 feet of F-1, yet none of these shears displace the drag aureole of F-1. Thus, they must predate development of much of the drag aureole. Alternatively, all three shears may be somewhat younger and all three (two on the footwall, one on the hanging wall of F-1) die out before reaching F-1. The preceding four examples further support the conclusion that prior to about 120 million years ago alternating displacements occurred on foliation shears and F-zone type structures.

The following examples of displacements along T-zones and shears parallel to foliation have no observed structural relationships from which to interpret their ages relative to F-1 and the Steeply Dipping shear. Thus, interpretation of their ages must be based on the similarities of their deformational styles with other structures of known age.

5. Drift No. 3A shears. - In Exploratory Drift No. 3A, shears associated with a metasediment unit offset a latite dike vertically about 4 feet down

to the east. In addition, two other shears at this locality show a cumulative, down-to-the-west vertical separation of about 0.5 foot (see figure IV-4). No surface exposures of these relationships have been observed.

6. T-10. - Recent exposures in the service spillway excavation show that T-10 offsets F-8 left laterally about 20 feet. This separation suggests down-to-the-east displacement. About 1,250 feet north of this exposure, F-1 cuts all shearing associated with T-10.

7. T-14. - Latite and diorite dikes exposed high on the upstream cutslope of the J-block show down-to-the-east vertical separations of about 15 feet across a shear which joins the main T-14 zone downslope. Subhorizontal jointing, small folds, and buckling of bedding planes suggests mostly dip-slip displacement.

Observations of T-14 in the auxiliary spillway were inconclusive with respect to the relative age of shearing along T-14 versus F-12, -13, and -33. These F-zones either deflect into T-14, die out near it, or possibly are cut by younger shearing within T-14.

8. T-25. - In the upper right abutment, shears associated with T-25 cut a latite dike designated F-22. Intrusive irregularities complicate estimates of separation at this intersection, but total vertical separation is probably no more than 5 or 6 feet. Subhorizontal joints and folds within the shear suggest down-to-the-west dip-slip displacement. Striations also suggest dip-slip movement. The relationships at this intersection are described in detail in another supplemental report (McMillan, 1978).

9. Maidu East shear zone. - Shearing associated with T-26 cuts both the Oregon Bar pluton and overlying Tertiary units. Mineralization of the shear zone within the pluton indicates that the zone existed prior to the youngest mineralization about 120 million years ago. However, neither the magnitude nor the sense of these older displacements are known. Displacements of overlying Tertiary units are down to the east and have vertical separations of up to 18 feet. Studies of materials infilling the Maidu East shear zone (O'Brient, 1978) suggest that displacement of the Tertiary units was intra-Mehrten. A tuff breccia unit of the Mehrten formation displaced by the Maidu East shear zone gave a K-Ar date of 8.7 million years. Thus, displacements have occurred on the Maidu East shear zone at least 110 million years apart.

Conclusion. - The vast majority of the preceding displacements are down to the east and appear to be mostly dip slip. As shown by the Maidu East shear zone and the Steeply Dipping shear these displacements occurred over a span of at least 110 million years. Thus, the presence of mostly dip-slip displacements, along north-northwest trending shears is not a clear indicator of Cenozoic faulting, for the apparent style of deformation expressed by both Mesozoic and Cenozoic deformations along these zones is identical. The first four examples in this section show that displacements of this style are postdated either by movement on F-1, another F-zone type structure, or both. The second four examples have no field relationships available from which to assess their relative ages. The last example, the Maidu East shear zone, has at least two periods of past displacement, one

more than 120 million years ago and a second most likely 8 or 9 million years ago. Whether the older displacements in this zone have the same sense of displacement as the younger displacements is not known.

Given the relationships of the foliation shears and the Steeply Dipping shear to F-1 in the left abutment, it may be reasonable to assume that at least some, if not all, of the displacement along the remaining foliation shears occurred at the same time as those on the Steeply Dipping shear; that is, prior to about 120 million years ago. However, it is also possible that some of the displacements on the four foliation shears not observed to intersect F-1 occurred in conjunction with displacement on the Maidu East shear zone; or are totally unrelated.

V. RELATIONSHIP OF DISPLACEMENTS ON T-ZONES AND FOLIATION SHEARS TO DISPLACEMENTS ON F-ZONES

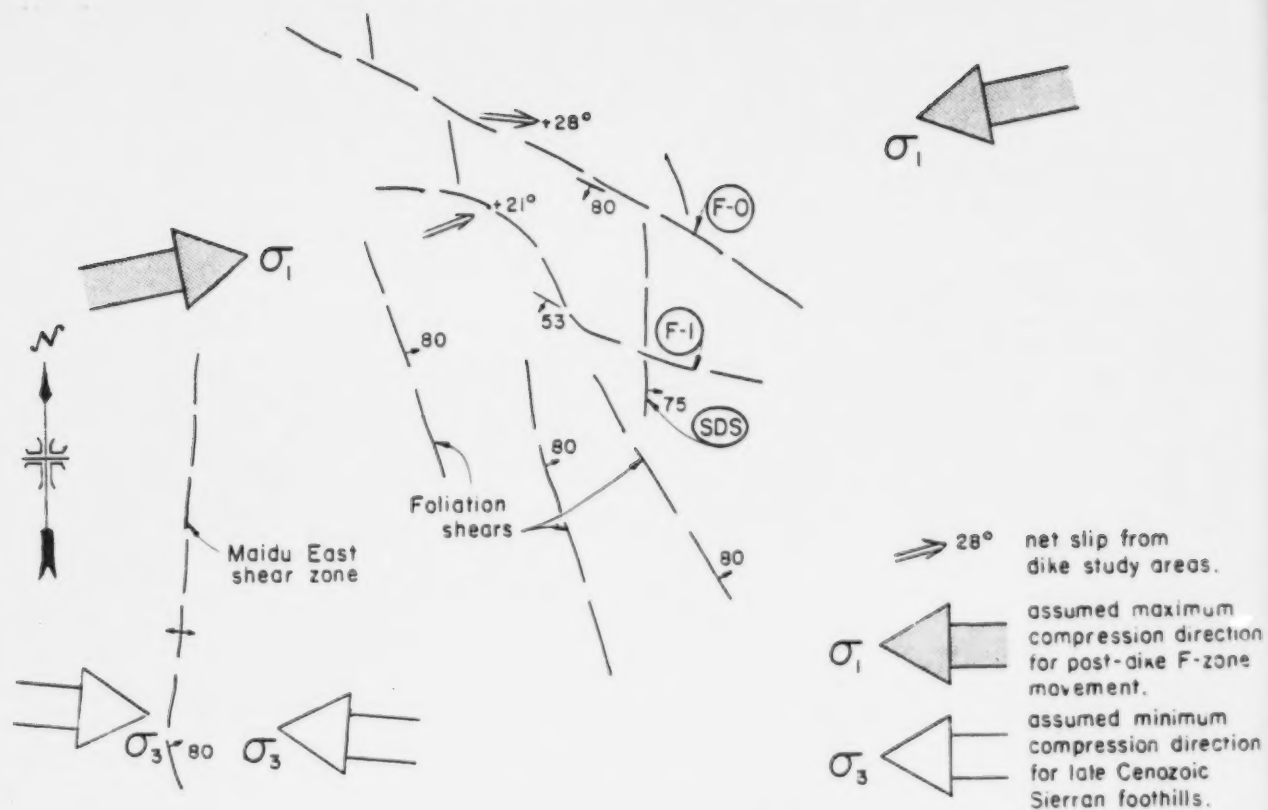
Introduction

Structural relationships along the Steeply Dipping shear and at the T-7/F-4 intersection demonstrate that alternating recurrent movement occurred on foliation shears and F-zones prior to about 120 million years ago. During this period, new F-zone and T-zone type shears formed, and some existing F-zones and T-zone shears had repeated movement(s). Thus, the stresses causing movement on these two sets of structures were either conducive to slip on both sets or the stresses were different and occurred in alternating pulses from about 150 to 120 million years ago.

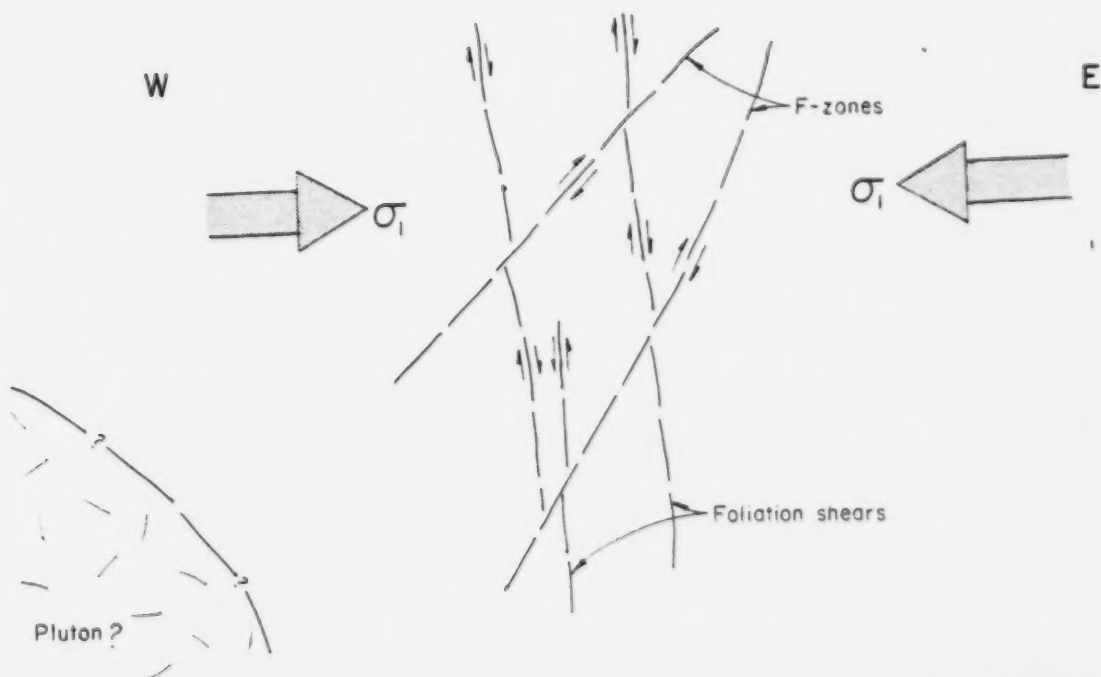
Dip-slip displacement on north-northwest trending structures is the style of deformation assumed to be expressed by offset late Cenozoic deposits within the western Sierran foothills (Woodward-Clyde Consultants, 1977). However, the stresses causing faulting of late Cenozoic deposits may be considerably different from those which caused the Mesozoic displacements of similar style on foliation shears.

Orientations of Stresses and Comparison of Displacements

Figures V-I(a) and V-I(b) illustrate the general geometrical relationships of F-zones and foliation shears as well as the net slip directions on F-1 and F-0 derived from post-dike displacements (McMillan and O'Brient, 1978). The dominant strike-slip component of these displacements and the relative orientations of F-1 and F-0 suggests that these displacements resulted from a maximum compression direction oriented nearly east-west to



(a) Schematic plan showing relationships of F-zones and foliation shears.



(b) Schematic E-W section showing relationship of F-zones, foliation shears and assumed max. compression for major F-zone movement.

Figure V-1

northeast-southwest. In this environment, the north-northwest trending and steeply east dipping foliation shears would be oriented nearly orthogonal to the direction of maximum compression. Displacements on foliation structures under these conditions would be "secondary" to displacements on F-zones and might be expected to have a right-lateral component.

The predominant slip direction on F-zones is reverse left-lateral oblique. Observed displacements along foliation structures appear to be mostly dip slip and may have small right-lateral components as indicated by the Steeply Dipping shear. A comparison of the magnitudes of observed displacements on F-zones and foliation shears suggests that displacements along F-zones may be an order of magnitude larger than those along foliation structures. For example, the maximum left-lateral separation of foliation units by F-1 is about 120 feet; and by F-0, perhaps as much as 200 feet. Under the condition of left-lateral, reverse-oblique slip on these F-zones, the separations would produce net slips approximately equal to the measured lateral separations. Maximum displacements of dikes and F-zones by foliation shears appears to be on the order of about 25 feet. For example, the lateral separation of F-8 by T-10 is about 20 feet; the vertical separation of dikes by T-14 is about 15 feet; the largest computed net slip on the Steeply Dipping shear is about 10 to 14 feet; and observed separations along other foliation shears are less than 4 feet. Assuming displacement on foliation shears is mostly dip slip, the separations listed above are essentially the net slips. Thus, maximum displacements on F-zones are probably on the order of 120 to 200 feet; and on foliation shears perhaps up to 25 feet.

Relationships to Late Cenozoic Faulting

In late Cenozoic time, the western Sierran foothills have had an assumed regional stress environment in which the minimum compressive stress is oriented east-west to east-southeast-west-northwest (Woodward-Clyde Consultants, 1977). Observed displacements of Tertiary units along the Maidu East shear zone are generally consistent with this postulated stress field and with displacements of late Cenozoic units elsewhere in the Sierran foothills. Major post-dike movements on F-zones require a maximum compressive stress oriented east-west to northeast-southwest. Since these movements more than 120 million years ago, the former maximum compression direction has apparently become the present day minimum compression direction. Thus, radically different stress conditions have produced apparently similar styles of deformation separated in time by more than 110 million years.

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6. McMillan, D. K., 1978, Analysis of Post-Latite Dike Faulting Along T-25 in the Right Abutment Keyway, Station 5+90, Auburn Dam

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APPENDIX A
Structural Analyses Of F-1

APPENDIX A - STRUCTURAL ANALYSIS OF F-1

Drawing No. 6 shows structural contours of F-0 and F-1 along with a geometrical analysis of F-1 and a compilation of observed slickensides on F-1.

F-1 Structural Analysis

Three separate analyses are shown on drawing No. 6. In each of the analyses, F-1 has been resolved into a series of component planes which together comprise an idealized fault composed of planar segments. Intersections of adjacent segments should represent geometrically preferred movement directions.

In the F-1 analysis the fault has been broken into three, four, or eight component planes. Component planes are represented on the drawing by large strike and dip symbols. The number or numeral at the left end of the strike line indicates both the plane's relative position along F-1 and also which of the three analyses it belongs to. Intersections of adjacent planes were determined by stereographic projection and are represented by heavy lines with diamond-shaped heads. Numbers or numerals at the tail of these lines indicate which two component planes intersect along that line. Component planes and their intersections in the three-plane analysis are indicated with Roman numerals I, II, and III. The four-plane analysis also utilizes planes I and II but refines plane III into components IIIa and IIIb.

Component planes and intersections for the three- and four-plane analyses are represented below the F-1 structural contours. Component planes and intersections of the eight-plane analysis are indicated by Arabic numbers 1 through 8 and shown above the surface trace of F-1.

Conclusion. - The intersections of component planes in all three analyses fall into two specific groups. The first and major group has an average bearing of S. 21° W. and plunges 52°. The second group represents the intersections associated with a unique portion of F-1, represented by component planes 5, IIIa or III. This second group has an average bearing of S. 18° E. and plunges 29°. Together, these intersection directions should represent the geometrically preferred direction of slip. Reverse slip along these intersections would produce left-lateral drag and offsets of foliation structures.

Slickensides on F-1

On drawing No. 6, slickensides observed on F-1 fault planes are shown along the excavation trace of F-1 and on figure 6-A, a lower hemisphere, equal area projection. Figure 6-B is a 1 percent area contour diagram of these data. Also shown on figures 6-A and 6-B is the trace of the average F-1 plane, as estimated from the structural contours. Most of the apparent scatter in the slickenside data relates to local variations in the orientation of F-1. Fitting the local orientation of the fault plane to these data eliminates this scatter.

Observed slickensides range mostly about two distinct bearings. One group bears west to S. 60° W.; the second bears about S. 7° W. Plunges range mostly from 15° to 50° depending on the orientation of the fault plane with respect to the slickenside bearing. As shown on figure 6-A, variation in the orientations of slickensides was encountered all along F-1. No variation in the direction of slickensides developed on different age elements of F-1 (e.g., dikes, quartz veins, or gouge seams) has yet been noted.

Slickensides with bearings near S. 65° W. are compatible with the net slip direction calculated in dike study area (McMillan and O'Brient, 1978), the net slip direction calculated using the lower latite dike and the Steeply Dipping shear at station 33+00, and with observations of left-lateral drag and separation on foliation structures intersecting F-1. They also indicate a major component of left-lateral strike-slip motion to the reverse slip on F-1. These slickensides are generally more pronounced than slickensides with other bearings.

Slickensides bearing near S. 7° W. are generally consistent with a slip direction along the intersections of F-1 component planes. Slip along this bearing is almost entirely dip slip, with little or no strike component. Reverse slip on this bearing would also produce left-lateral separation and drag of the metamorphic foliation. Slickensides with this bearing are generally less pronounced than slickensides with more westerly bearings.

Conclusion. - Slickensides observed along F-1 suggest two directions of slip, both of which occurred along the entire length of the fault. One slip direction is dominantly strike slip; the other is dominantly dip slip. Both slip directions produce left-lateral separations of foliation structures if the slip has a reverse component.

Net Slip for Post-Steeply Dipping Shear Movement on F-1

The youngest F-1 movement produced a 2- to 3-foot left-lateral separation of the Steeply Dipping shear. This movement is post-major movement on F-1 as shown by comparison with offsets of foliation structures in the left abutment. To date, no relationship fixes the lower age boundary on this

movement, but net-slip solutions which limit the magnitude can be computed using the lateral separation of the Steeply Dipping shear.

Net Slip Solutions Using the Lower Latite Dike and the Steeply Dipping Shear. - Figure A-I(a) illustrates the rake of the lower latite dike on both the F-1 attitude used for the Dike Study net slip solution and on the overall average F-1 attitude. Figure A-I(b) is an orthographic solution for net slip on the overall average F-1 using a 2.5-foot left-lateral separation of the Steeply Dipping shear and a 2-foot right-lateral separation of the lower latite dike. Net slip magnitude is 2.6 to 3.0 feet with a rake of 56° to 59° depending on the rake used for the Steeply Dipping shear.

Assuming there is no horizontal separation of the lower dike, the slip when coupled with the 2.5-foot separation of the Steeply Dipping shear is constrained to occur along the plunge of the F-1/lower dike intersection (rake = 34°) and its magnitude is about 2.5 feet. Both of the above net slips are reverse with left-lateral oblique components.

Net Slip Solutions Using Slickenside Orientations and the Dike Study Net Slip Direction with the Steeply Dipping Shear. - As discussed previously, the preponderance of two slickenside directions has been noted. Figure A-II(a) illustrates the rake of these two slickenside directions on the overall average F-1, the average rakes of the Steeply Dipping shear on F-1, and the rake of the net slip vector for post-dike slip determined in the dike study.

Figure A-II(b) shows the magnitude of net slip on F-1 for each of the rakes determined in figure A-II(a). These magnitudes express the full range of

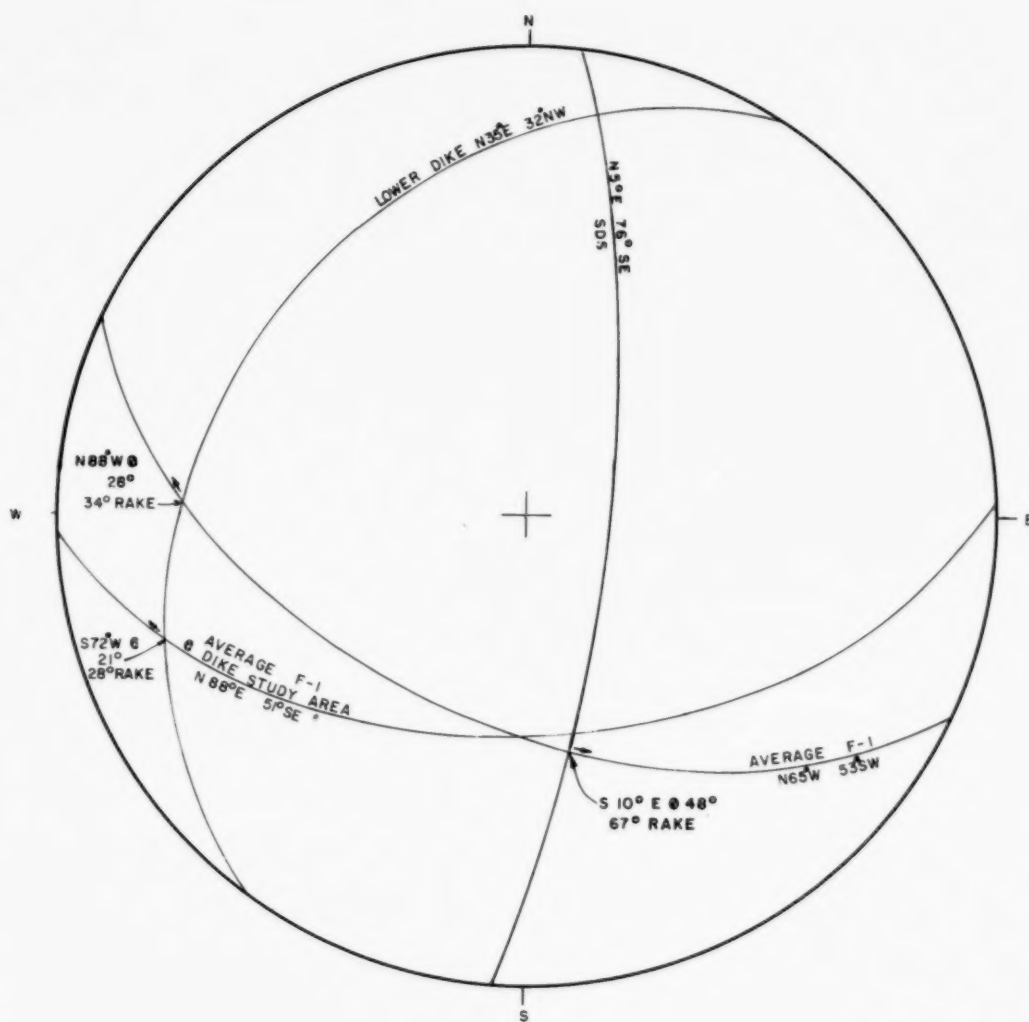


Fig.AI(a) Stereographic determination of rake relationships on assumed average F-1 and the F-1 orientation used for dike study. (Lower Hemisphere, equal area projections.)

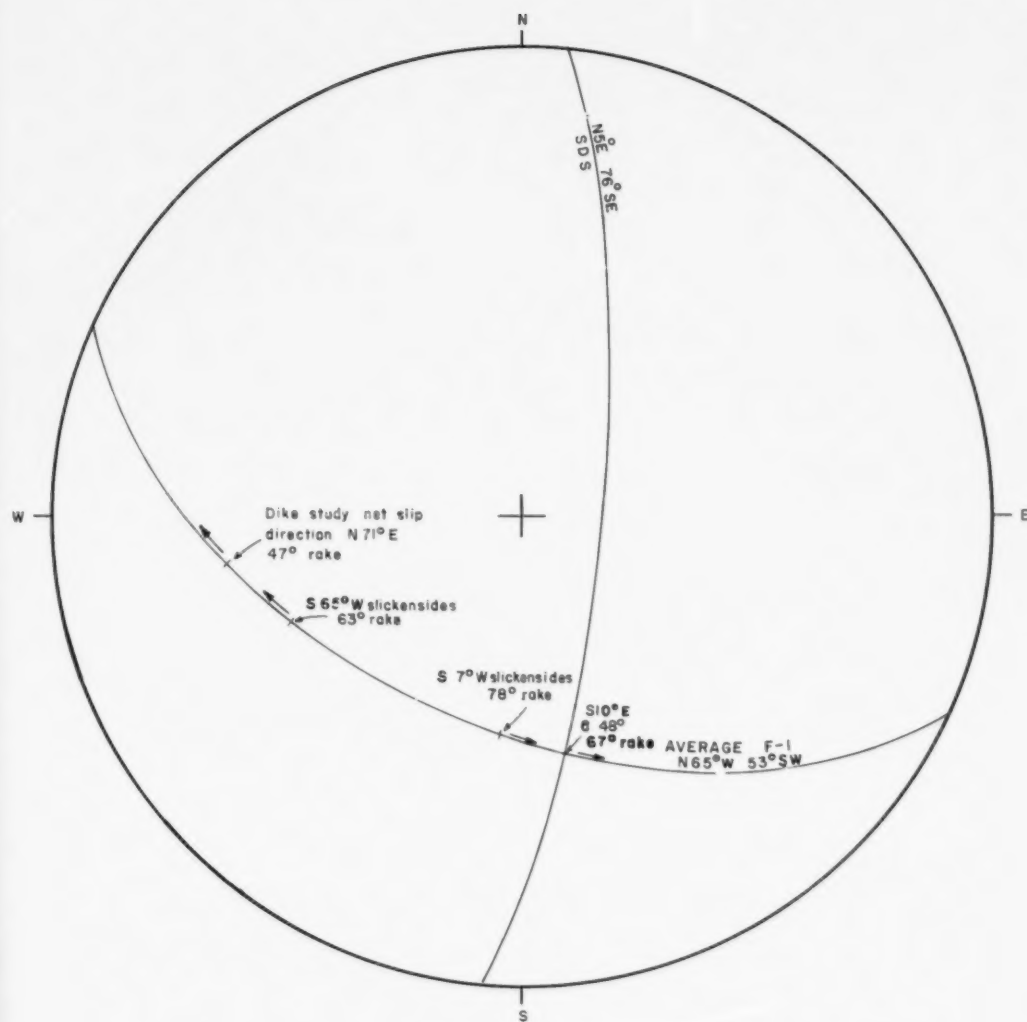


Fig.A-II(a) Stereographic determination of rakes on F-1 for slickensides, S.D.S., lower latite dike and Dike Study net-slip solution (Lower Hemisphere, equal area projections).

RAKE
STUDY
ON AVE

OBSE
BEAR
63°

ON
BY
7

Fig.A-II(b)

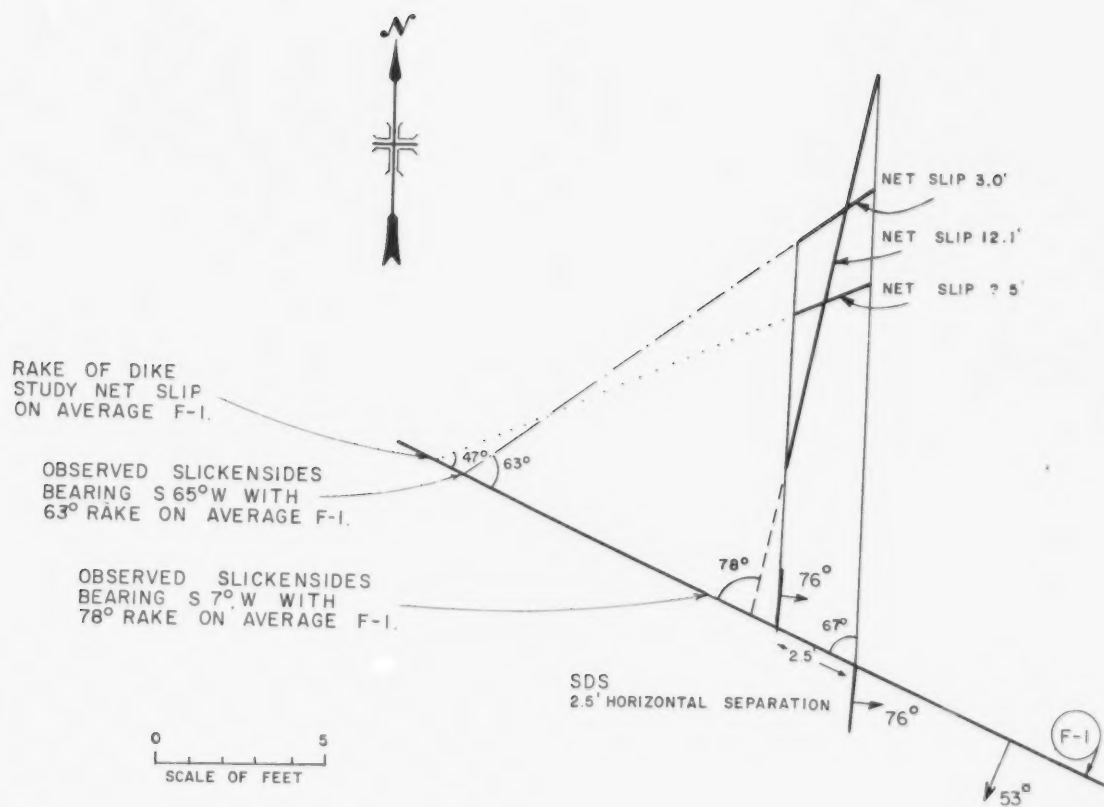


Fig.A-II(b) Orthographic solution for maximum and minimum net slip on F-1 using observed slickensides and lateral separation of the S.D.S.

possible post-Steeply Dipping shear net slip on F-1. The amount of net slip for the youngest movement on F-1 ranges from 12.1 feet assuming dip-slip slickensides to a minimum of 2.5 feet using strike-slip slickensides. Due to the small angle (11°) between dip-slip slickensides and the rake of the Steeply Dipping shear, the magnitude of net slip varies greatly with small deviations from these rakes. The solution for strike-slip movement on F-1 agrees well with the magnitudes and directions of movement determined for net slips in figure A-1(b). All of the above solutions require reverse-oblique slip on F-1.

APPENDIX B
Accuracy Of Net Slip Solutions

APPENDIX B - ACCURACY OF NET SLIP SOLUTIONS

The accuracy of net slip computations for this report is analyzed and tabulated below. Two cases are distinguished: (1) solutions with assumed slip directions and (2) solutions using two offset features which yield both net slip direction and magnitude.

Solutions With an Assumed Slip Direction

Figures 4-F and 4-I on drawing No. 4 show orthographic solutions of net slip for elements of F-1 and mineralized veinlets. All of these solutions use an assumed net slip direction with a rake of 70° to the south on the Steeply Dipping shear. This slip direction represents one boundary of the range of slip directions indicated by slickensides and slip directions computed using two offset features. The 70° boundary was chosen for computation because it is closest to being along the intersection of offset features, and thus provides the largest values of net slip. Similarly, rakes of mineralized veinlets are boundary values nearest the slip direction, based on analysis of measured strikes and dips. For F-1, both the upper and lower boundaries of rake values are considered.

Figure B-I shows the geometrical relationships between elements in the net slip computation and the equations used to analyze variations. Variation in the magnitude of net slip ($\overline{BC}$) is best expressed by changes in the angle C, which describes the relationship between the rake of the net slip (B) and the rake of the offset feature (A). For small values of C ($< 10^\circ$ to 15°),

small angular changes will produce large changes in net slip magnitude. As C increases, the rate of change in net slip magnitude with respect to change in C decreases.

Calculations shown in tables B-1, -2, and -3 describe the variation in net slip magnitude with changes in C for Quartz veins No. 1 and 2 and F-1. These data are shown in graphical form on figures B-II, -III, and -IV. The calculations indicate that a range of variation for C between -4° and $+10^{\circ}$ encompasses a plus or minus 40 percent variation in net slip magnitude. The asymmetric variation of C reflects the choice of base values for A and B. Values of -4° and $+10^{\circ}$ are considered conservative limits for this variation, based on analysis of measured strikes and dips.

A range of plus or minus 40 percent for net slip magnitude produces different absolute ranges of variation for each of the net slip solutions. These variations and the overlap of each of the net slip solutions are summarized on table B-4. Although there is an overlap in the ranges of individual solutions, the relative order of offset between individual features is unchanged, even with a 40 percent variation in the magnitude of net slip. Thus, the veins are of different ages, with movement on the Steeply Dipping shear occurring between emplacement of each.

Table B-1. - Variation of net slip of quartz vein No. 1

Base condition - A = 53° B = 110° C = 17°

$\overline{AB}$ = 1.2 ft $\overline{BC}$ = 3.3 ft

Case No. 1 - Vary C with B; hold A constant.

Case No. 2 - Vary C with A; hold B constant.

Case No. 3 - Vary C; Vary A and B each by one-half amount.

Case No.		A (°)	C (°)	B (°)	$\overline{AB}$ (ft)	$\overline{BC}$ (ft)	$\overline{BC}$ (percent of base)
1	Base	53	17	110	1.2	3.3	100
		53	21	106	1.2	2.7	82
							+C
		53	25	102	1.2	2.3	70
		53	29	98	1.2	2.0	61
		53	13	114	1.2	4.3	130
		53	9	118	1.2	6.1	185
		53	5	122	1.2	11.0	333
							-C
2	Base	53	17	110	1.2	3.3	100
		49	21	110	1.2	2.5	76
		45	25	110	1.2	2.0	61
		41	29	110	1.2	1.6	48
							+C
		57	13	110	1.2	4.5	136
		61	9	110	1.2	6.7	203
		65	5	110	1.2	12.5	379
							-C
3	Base	53	17	110	1.2	3.3	100
		51	21	108	1.2	2.6	79
		49	25	106	1.2	2.1	64
		47	29	104	1.2	1.8	55
							+C
		55	13	112	1.2	4.4	133
		57	9	114	1.2	6.4	194
		59	5	116	1.2	11.8	358
							-C

Table B-2. - Variation of net slip of quartz vein No. 2

Base condition - A = 57° B = 110° C = 13°

$\overline{AB}$ = 1.8 ft $\overline{BC}$ = 6.7 ft

Case No. 1 - Vary C with B; hold A constant.

Case No. 2 - Vary C with A; hold B constant.

Case No. 3 - Vary C; vary A and B each by one-half amount.

Case No.		A (°)	C (°)	B (°)	$\overline{AB}$ (ft)	$\overline{BC}$ (ft)	$\overline{BC}$ (percent of base)
1	Base	57	13	110	1.8	6.7	100
		57	17	106	1.8	5.2	78
		57	21	102	1.8	4.2	63
		57	25	98	1.8	3.6	54
		57	9	114	1.8	9.7	145
		57	5	118	1.8	17.3	258
							-C
2	Base	57	13	110	1.8	6.7	100
		53	17	110	1.8	4.9	73
		49	21	110	1.8	3.8	57
		45	25	110	1.8	3.0	45
		41	29	110	1.8	2.4	36
		61	9	110	1.8	10.1	151
		65	5	110	1.8	18.7	279
		67	3	110	1.8	31.7	473
							-C
3	Base	57	13	110	1.8	6.7	100
		55	17	108	1.8	5.0	75
		53	21	106	1.8	4.0	60
		51	25	104	1.8	3.3	49
		59	9	112	1.8	9.9	148
		61	5	114	1.8	18.1	270

Table B-3. - Variation of net slip of F-1

Base condition - A = 39° B = 110° C = 31°

 $\overline{AB} = 8.0$ ft $\overline{BC} = 9.8$ ft

Case No. 1 - Vary C with B; hold A constant.

Case No. 2 - Vary C with A; hold B constant.

Case No. 3 - Vary C; Vary A and B each by one-half amount.

Case No.		A (°)	C (°)	B (°)	$\overline{AB}$ (ft)	$\overline{BC}$ (ft)	$\overline{BC}$ (percent of base)
1	Base	39	31	110	8.0	9.8	100
		39	35	106	8.0	8.8	90
		39	39	102	8.0	8.0	82
		39	43	98	8.0	7.4	76
		39	47	94	8.0	6.9	70
		39	27	114	8.0	11.1	113
		39	23	118	8.0	12.9	132
		39	19	122	8.0	15.5	158
		39	15	126	8.0	19.5	199
		39	11	130	8.0	26.4	269
2	Base	39	31	110	8.0	9.8	100
		35	35	110	8.0	8.0	82
		31	39	110	8.0	6.5	66
		27	43	110	8.0	5.3	54
		23	47	110	8.0	4.3	44
		43	27	110	8.0	12.0	122
		47	23	110	8.0	15.0	153
		51	19	110	8.0	19.1	195
		55	15	110	8.0	25.3	258
		59	11	110	8.0	35.9	366
3	Base	39	31	110	8.0	9.8	100
		37	35	108	8.0	8.4	86
		35	39	106	8.0	7.3	75
		33	43	104	8.0	6.4	65
		31	47	102	8.0	5.6	57
		41	27	112	8.0	11.6	118
		43	23	114	8.0	14.0	143
		45	19	116	8.0	17.4	178
		47	15	118	8.0	22.6	231
		49	11	120	8.0	31.6	322

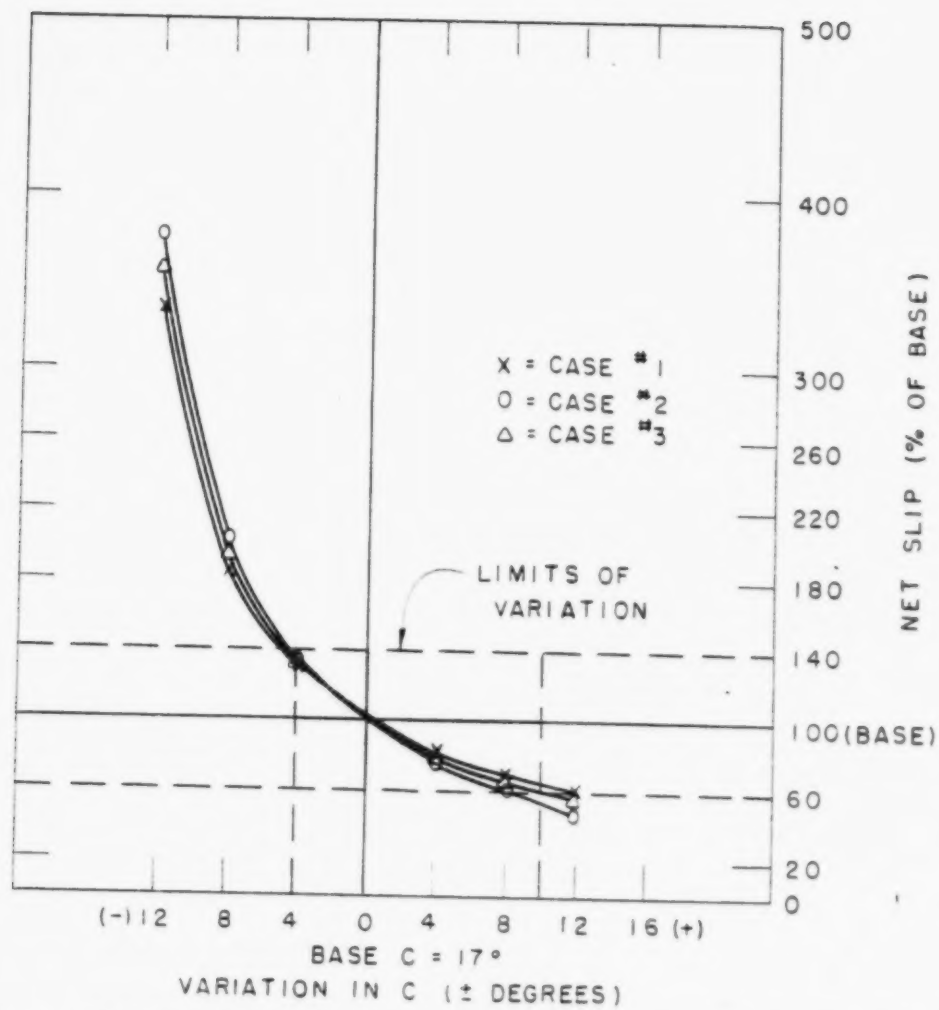


FIGURE B-II-VARIATION OF NET SLIP OF QUARTZ VEIN NO. 1

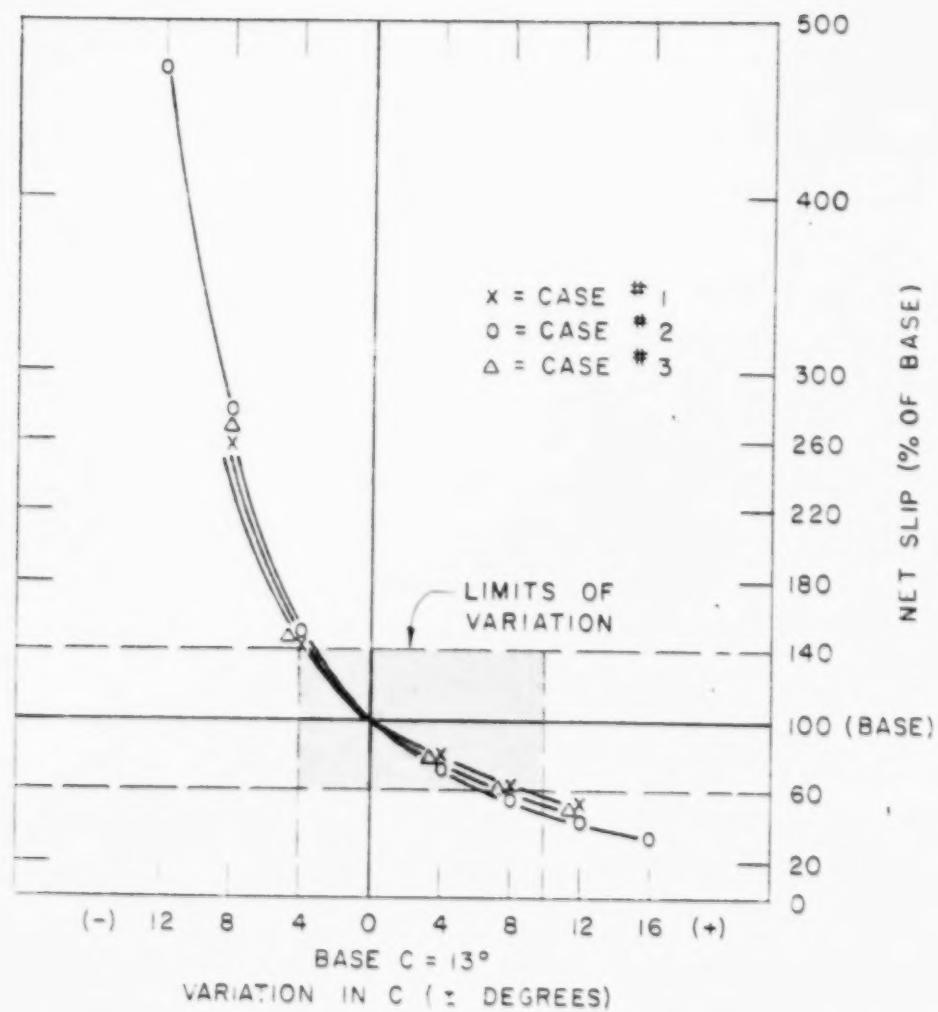


FIGURE B-III—VARIATION OF NET SLIP OF QUARTZ VEIN NO. 2

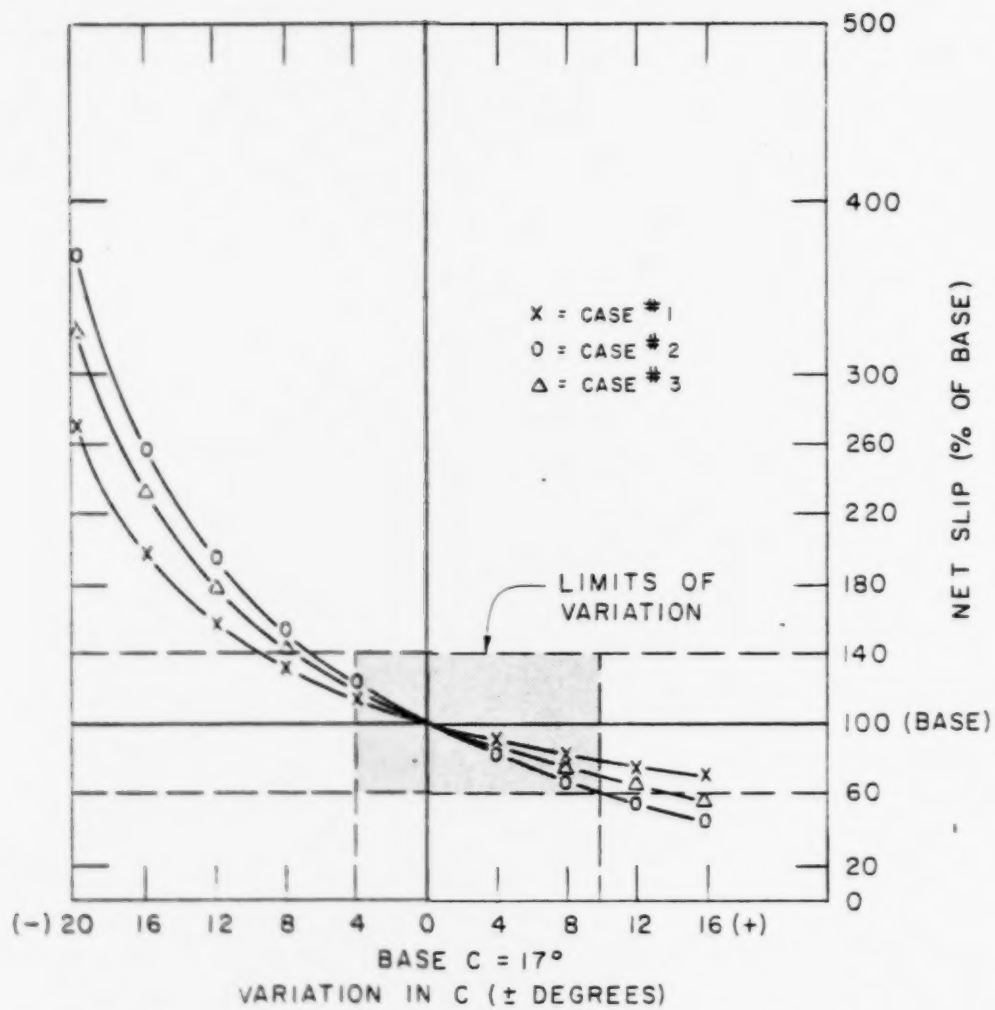
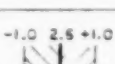
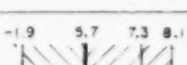


FIGURE B-IV-VARIATION OF NET SLIP OF F-1

TABLE B-4
RANGES OF VARIATION FOR NET SLIPS ON SDS

OFFSET FEATURE	LIMIT OF VARIATION	RANGE OF NET SLIP (FEET)			
		0	5	10	15
QUARTZ VEIN #1	±40%				
QUARTZ VEIN #2 *	"				
EPIDOTE VEIN *	"				
CALCITE VEIN *	"				
F-1 DIKE	BOUNDED BY LIMITS OF F-1 ORIENTATION				
F-1 CSC AUREOLE	"				
F-1 QUARTZ VEIN (POSSIBLE 33% REDUCTION IN LATERAL SEPERATION)	"				
F-29/ VERTICAL SHEAR	EST. MAX. 30%				
F-35/ VERTICAL SHEAR	"				

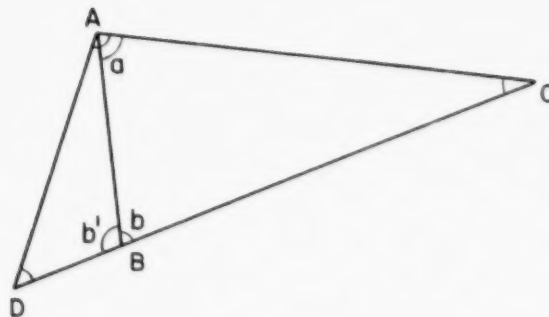
Net slips and variations computed with equations in Appendix B.
* May not represent total net slip; veins do not cross all SDS shears.

Solutions With Two Offset Features

Figures 4-G and 4-H (drawing No. 4) are orthographic solutions for net slip on the Steeply Dipping shear using the upstream dike, F-1, and three quartz-healed shears. Each of these solutions utilizes two features of opposing orientations and produces both net slip magnitude and direction. A numerical analysis of variation for these solutions is not included here; however, some qualitative comments on their accuracy follow.

The general geometric relationships and equations for computing net slip with two offset features are shown in figure B-V. The lateral separations of offset features are shown by lines $\overline{DC}$ and its components $\overline{DB}$ and $\overline{BC}$; the rakes of offset features and net slip direction by angles D , b , and C . The method of computation of net slip varies depending upon the relative sense of displacement of the offset features, i.e., for two features showing the same or opposite senses of separation. If the offset features show opposite senses of separation, the net slip $\overline{AB}$ with rake b , is computed using separations $\overline{DB}$ and $\overline{BC}$ with rakes D and C , respectively. If the offset features have similar senses of separation, the net slip $\overline{AD}$ with rake D is computed using separations $\overline{DB}$ and $\overline{DC}$ with rakes b and C , respectively.

The equations for opposite separations on figure B-V were used to check the net slip determinations shown in figures 4-G and 4-H on drawing No. 4, except for the solution with the upstream dike and the Vertical shear, for which the equations for similar separations are applicable.



A. Net slip for offset features with opposite senses of separation.

Given: Separation $\overline{DB}$ with rake D
Separation BC with rake C

Then: $A = 180^\circ - (D+C)$
 $\overline{DC} = \overline{DB} + \overline{BC}$

To find net slip $\overline{AB}$ with rake b:

$$\text{Equation 1} \quad \overline{AC} = \frac{\sin D \cdot \overline{DC}}{\sin A}$$

$$\text{Equation 2} \quad \overline{AB} = \sqrt{(\overline{BC})^2 + (\overline{AC})^2 - 2(\overline{BC})(\overline{AC})(\cos C)}$$

$$\text{Equation 3} \quad b = \arcsin\left(\frac{\overline{AC} \cdot \sin C}{\overline{AB}}\right)$$

B. Net slip for offset features with similar senses of separation.

Given: Separation $\overline{DC}$ with rake C
Separation DB with rake b

Then: $a = 180 - (b+c)$
 $b' = 180 - b$
 $\overline{BC} = \overline{DC} - \overline{DB}$

To find net slip $\overline{AD}$ with rake D:

$$\text{Equation 1} \quad \overline{AB} = \frac{\sin C \cdot \overline{BC}}{\sin A}$$

$$\text{Equation 2} \quad \overline{AD} = \sqrt{(\overline{AB})^2 + (\overline{DB})^2 - 2(\overline{AB})(\overline{DB})(\cos b')}$$

$$\text{Equation 3} \quad D = \arcsin\left(\frac{\overline{AB} \cdot \sin b'}{\overline{AD}}\right)$$

Figure B-V-Equations for Computation of Net Slip
with Two Offset Features.

If maximum values of separation and rake are input into the computations, then the net slip will also be a maximum for any reasonable reduction in separations or rakes. The effect on the net slip of reducing the rake of an offset feature is shown by the variation of net slip between the upper and lower limits of orientation for F-1 (figure 4-G, drawing No. 4). An 11° reduction in the rake of F-1 on the Steeply Dipping shear reduces the magnitude of net slip by 20 percent and the rake of net slip by 12° . The 11° range in the rake of F-1 represents a reasonable maximum range for variations in its orientation. Similar values apply to variations in orientation for other features used to compute net slip.

Most measured separations are maximums based on observations of correlative offset features at two or more stages of excavation. Separations may vary as much as 10 percent less than the maximum values used for computation.

A qualitative analysis of reasonable variation from separations and rakes used to compute net slip with two offset features suggests that these net slip magnitudes are accurate to within 20 to 30 percent. Net slip rakes are thought to be accurate within 5 to 10° with the most reasonable and largest potential variations occurring in a manner which would increase the rake of net slip. Variations which reduce the rake of net slip below about 70° are not considered credible.

APPENDIX C

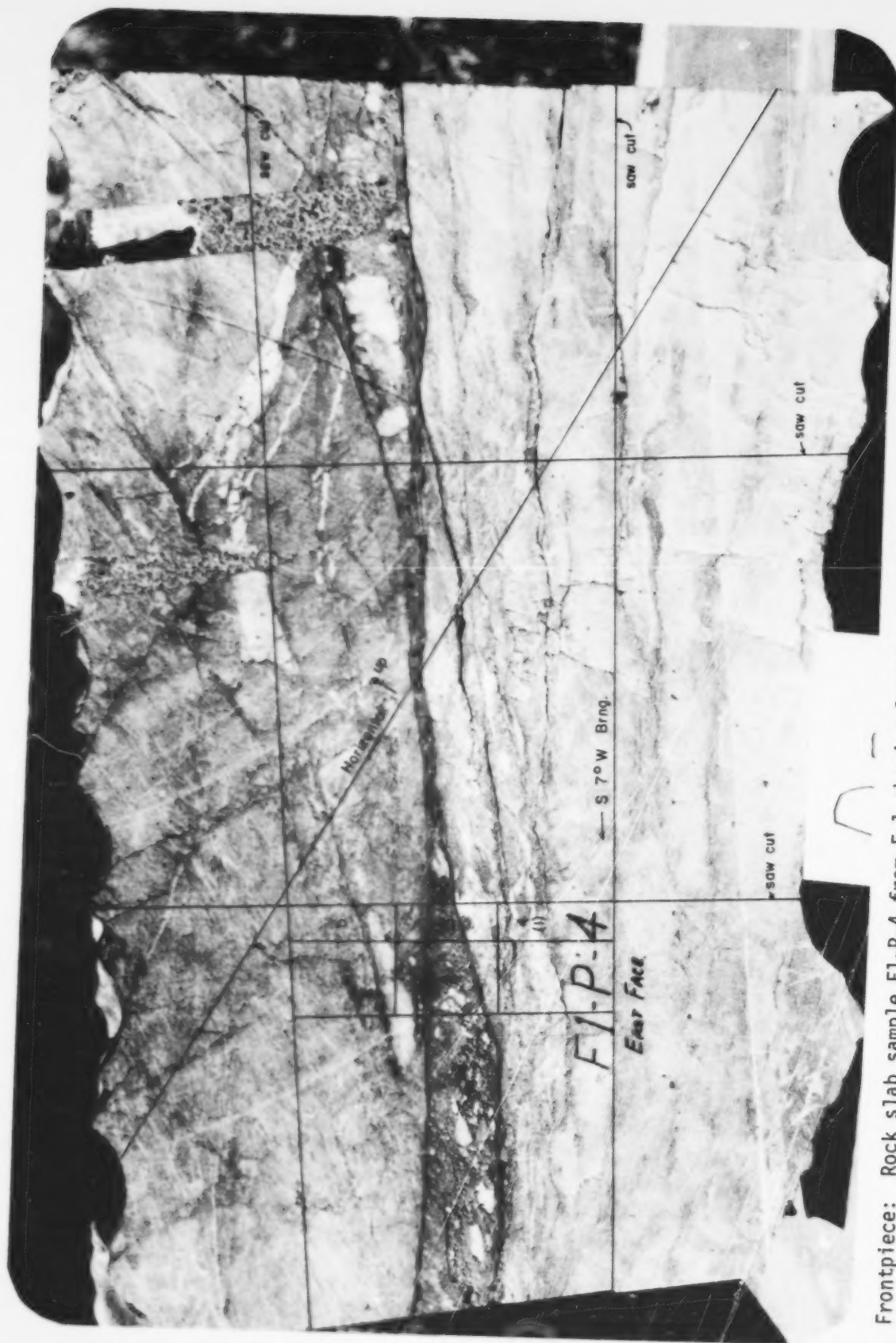
Gouge and Associated Deformation
Along Fault F1, Auburn Damsite

Gouge and Associated Deformation along Fault F1
Auburn Damsite

by
Robert R. Compton

for the
U. S. Bureau of Reclamation
Auburn, CA

July 1978



Frontpiece: Rock slab sample F1-P-4 from F-1 showing locations where thin sections numbered 1 to 5 obtained.

Gouge and Associated Deformation along Fault F1,
Auburn Damsite

by Robert R. Compton

Materials studied. This study had the purpose of interpreting timing of movements along F1, the principal fault in the foundation proposed for the Auburn Dam. A segment of the fault zone had been impregnated with a monomer, set by polymerization, and sawed out intact, so that the gouge and associated features could be examined completely in three dimensions. The recovered sample, designated F1-P-4, measured approximately 2 X 15 X 24 inches. It was sawed into blocks in order to prepare thin sections, five of which were made by Mr. Ruperto Laniz, who impregnated the thin section slabs repeatedly to preserve friable materials and all open spaces. The resulting oriented thin sections thus provide a means of identifying details of the fault zone and of matching them exactly from microscope view to F1-P-4 and thereby to the fault in the foundation.

The locations and orientations of the thin sections have been marked on the slabs of sample F1-P-4. The thin sections, numbered 1 to 5, F1-P-4, cover these parts of the fault zone:

1. The footwall quartz body and adjoining border of the gouge.
2. All of the gouge zone and a small part of each wall rock, the section being oriented at right angles to all the other sections.
3. All of the gouge and a small part of each wall rock.
4. The quartz body of the footwall, next to the gouge.
5. The schist of the hanging wall, 1 inch from the gouge.

General description. The gouge constitutes a sharply delineated zone between the sericite-ankerite schist of the hanging wall and the quartz body making up the footwall at this locality. The two boundaries of the gouge zone cut across mineral grains, rock fabrics, and other small-scale features of the wall rocks, a relation that can be seen in thin section as well as in the large sample. The gouge zone varies considerably in thickness, from less than 0.05 inch at the north end of the sample to 1.5 inches at the south end. The zone is made especially distinctive by sheeted bodies of redbrown clay (pale yellow in thin section) that form the outer parts of the zone and thus border the adjoining wall rocks. Color slides 1A and 1B show this clay clearly and also show an open crack that typically lies in the outer part of the clay or between the clay

and the wall rock. Between the bordering clay bodies, the gouge is dark gray and carries numerous angular to rounded fragments of quartz, albite, and schist.

Similar but much thinner gouge zones occur here and there along minor faults in the hanging wall of the large sample, and some of these gouge bodies also have associated brown clay and open cracks. These lesser faults commonly cut across and displace foliation and veins in the hanging wall schist.

The gouge under the microscope. The yellow clay that borders the gouge differs distinctly from the clastic gouge forming the main part of the gouge zone. The yellow clay generally contains no mineral fragments and shows a foliated crystal fabric that is typically parallel to the separate clay sheets making up the clay bodies. The individual sheets, however, are discontinuous, pinching and swelling along their length and ending in tapered or rounded forms. The bodies give the impression that the border of the gouge episodically separated from its walls and the space was filled with the clay. The discontinuous nature of the clay sheets suggests that the openings were small-- perhaps several millimeters in length for the average case. One can only guess at the clay species; the refractive indices and birefringence suggest it could be a ferromagnesian illite-chlorite (or smectite) interlayer.

Progressing into the gouge from the walls, the clay sheets become more and more deformed, both by folding and faulting. As color slides 2A and 2B show, the innermost clay sheets are even broken and strewn randomly in the clastic part of the gouge, with threadlike wisps becoming aligned locally between the larger fragments of quartz and other minerals. These relations suggest strongly that movements have affected the gouge episodically during the period in which the yellow clay was forming along the gouge walls.

The inner, clastic part of the gouge consists of a variety of mineral fragments set in an abundant matrix of fine (2 microns and less) grains. By far most of the sand or silt-sized clasts are quartz, although schist and ankerite fragments of those sizes can be seen locally. The finer materials, on the other hand, consist mainly of comminuted sericite-ankerite schist, giving the impression that most of the gouge was formed by fine-grinding of the hanging wall. Albite grains from the footwall are fairly common, and pyrite, which is especially abundant in the hanging wall, occurs both as broken or milled grains and as euhedra (which were evidently strong enough to withstand movements in the soft sericite-carbonate matrix). Color slide 1A shows one of these euhedra. Some calcite and fairly numerous quartz grains, too, were unstrained even though they were broken out of one of the walls and incorporated in the fine gouge.

Color slides 3A and B show several of these unstrained quartz fragments. One may also find grains of all mineral species that underwent large strains before or during their incorporation into the gouge.

The wall rocks. The schist of the hanging wall consists mainly of sericite and ankerite (presumably the "ferrian dolomite" of other reports), and also contains considerable pyrite and quartz. No chromian mica ("mariposite") was seen in the wall rock, though fragments were seen in the gouge. The quartz body along the footwall includes considerable albite and, locally, pyrite, chlorite, and sericite.

The hanging wall schist is far more deformed than the quartz body. Both rocks show a range of deformational features suggesting episodic movements during the period when the principal minerals formed (the "mineralization" of other reports). Ankerite, for example, occurs in greatly deformed grains, in moderately deformed (twinned) grains, and as untwinned euhedra. Quartz in the footwall is generally moderately strained (with uneven extinction) but locally greatly strained (with abundant deformation lamellae, or polygonized). Color slides 4A and B, on the other hand, show a quartz-chlorite vein that is almost undeformed, and several of the thin sections show calcite veins in which calcite is only locally twinned (a very low state of strain).

Microfaults, too, appear to have formed over an appreciable period following the growth of the various minerals. The most common of them cut obliquely across the sericite-ankerite schistosity, as indicated in color slides 5A and B. These earlier faults show no sign of brecciation or gouge formation. Later faults have clay gouge along them, even thin sheets of the yellow clay like that in the main gouge zone, and some have open cracks like the main gouge zone. As color slides 5A and B show, pyrite was locally broken and strewn along the faults.

Conclusions. The petrographic relations and minerals indicate a long period of deformation associated with the F1 fault, part of this deformation taking place when the principal minerals--quartz, ankerite, sericite, pyrite, and calcite--were forming, and part taking place later. The evidence for the later deformation can be reviewed as follows:

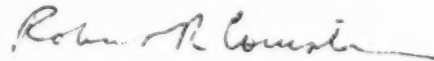
1. The walls delineating the gouge cut across mineral grains of both wall rocks.
2. Grains of quartz, albite, ankerite, calcite, pyrite, sericite schist, and chromian mica in the gouge are distinctly fragmental.
3. Even the fine sericite and carbonates of the gouge matrix appear to be

fragmental.

4. Clays crystallized in the gouge but evidently at its margins and probably in open spaces along the walls.
5. Deformation of these clays indicates progressive deformation since the clay sheets began to form.

The indication that clays formed in open spaces suggests, in turn, that the late-stage movements along the fault took place at a comparatively shallow depth. Lack of deformation of quartz and calcite fragments included in the gouge suggest that these grains were incorporated when temperatures were low and confining pressure was low. These relations, along with those just enumerated, indicate strongly that the F1 fault has undergone episodic movement since the period of mineralization that formed the principal minerals of the wall rocks.

Respectfully submitted,



Robert R. Compton

Professor of Geology

Department of Geology

Stanford, Calif. 94305

Enclosures : Ten color slides as referred to in the report, with line drawings identifying the principal features in them and showing the location of the slides in the thin sections.

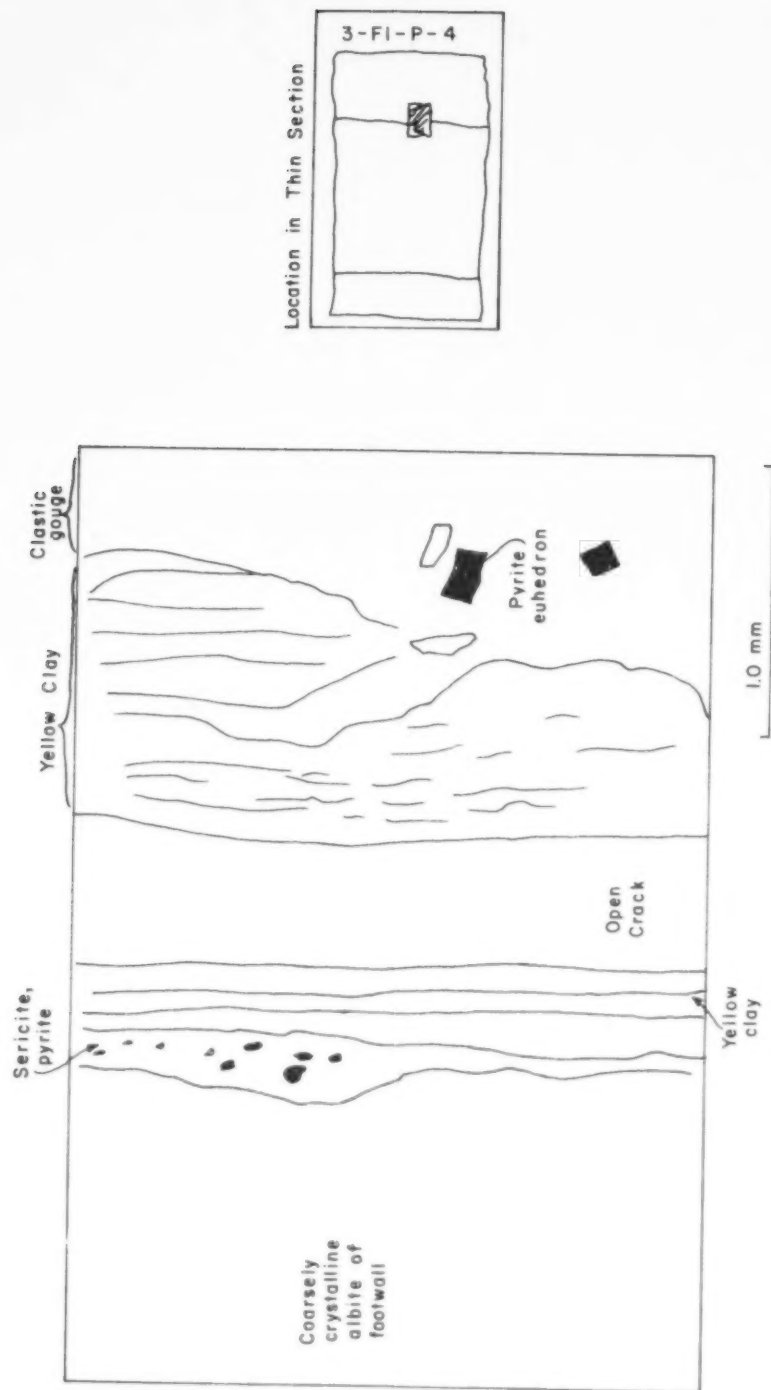


Figure 1 - Color Slides 1A, B

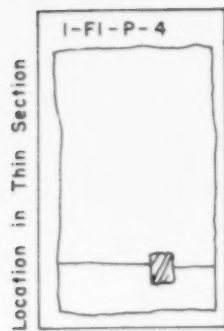
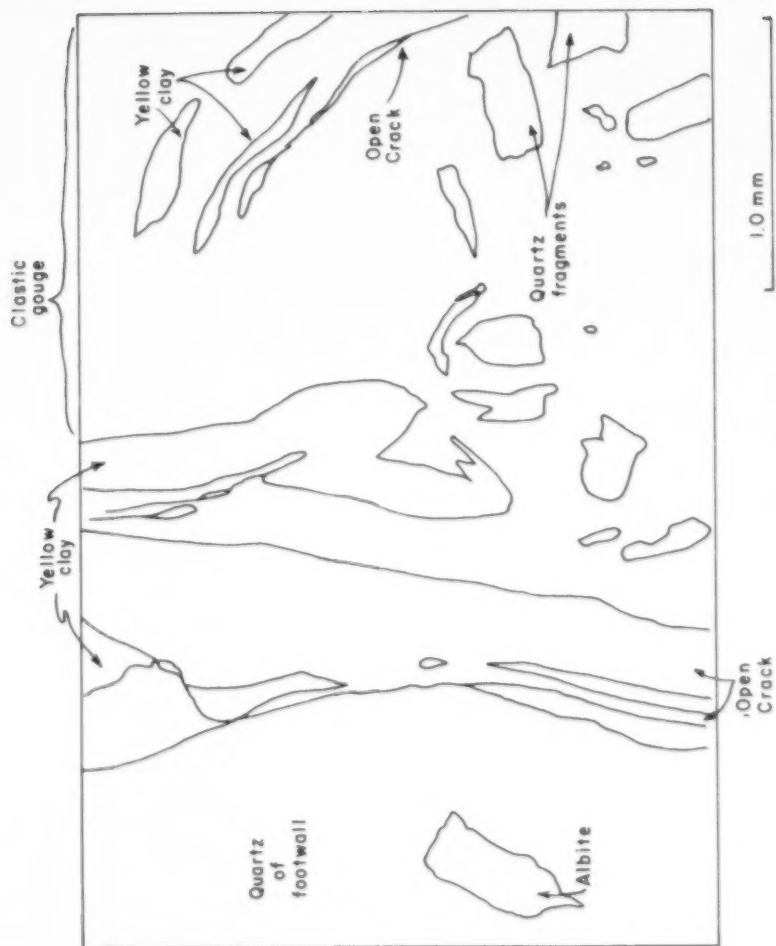


Figure 2 - Color Slides 2A,B

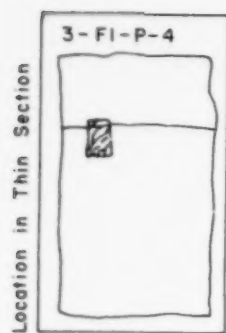
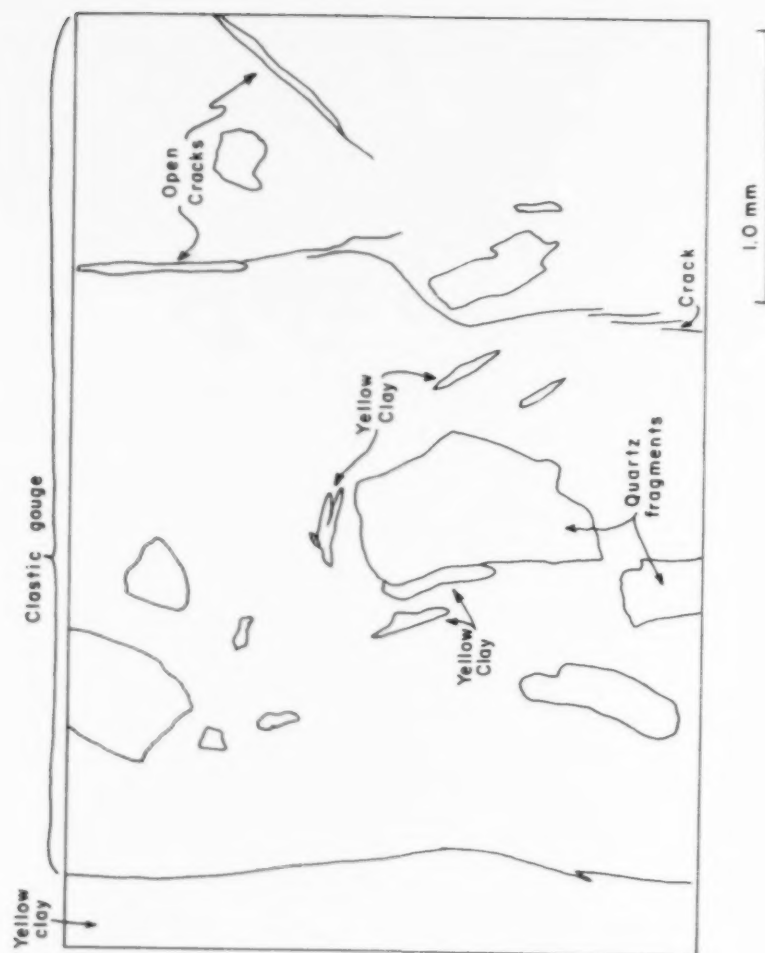


Figure 3 - Color Slides 3A, B

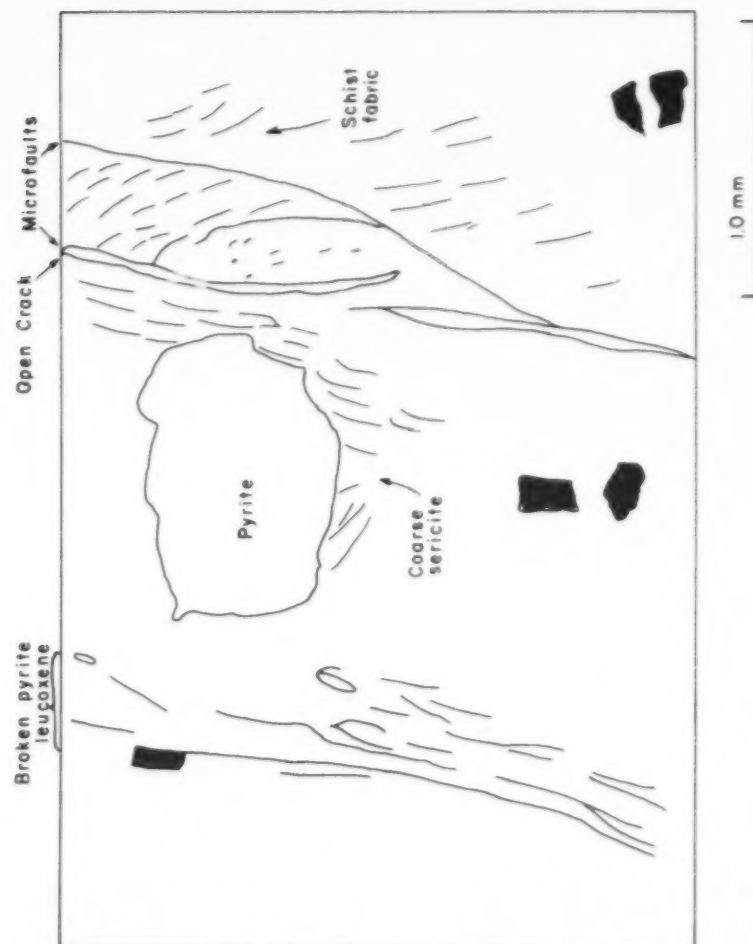
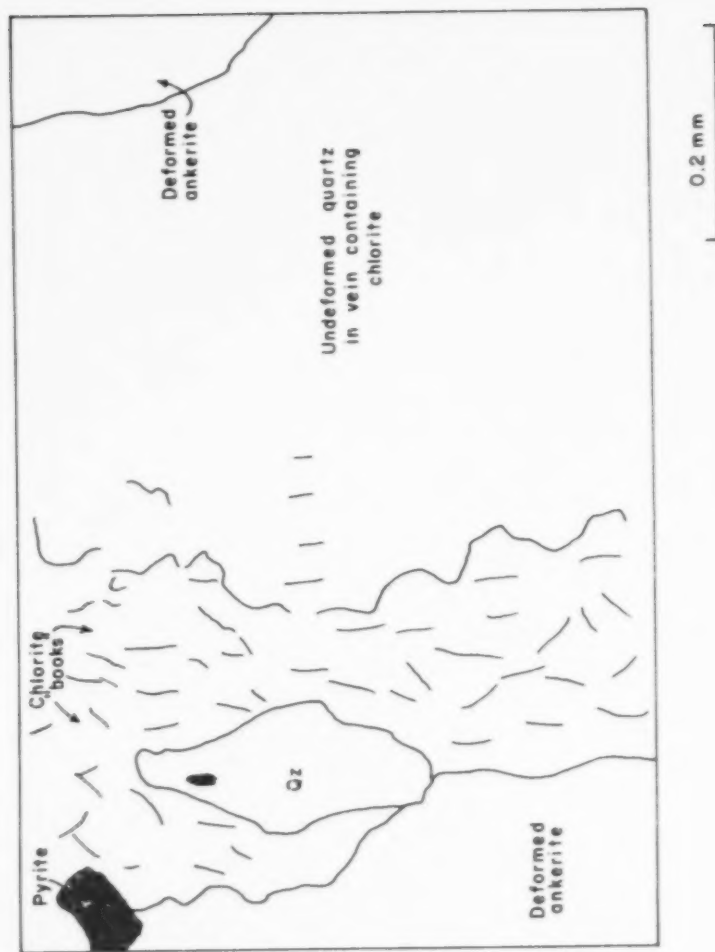
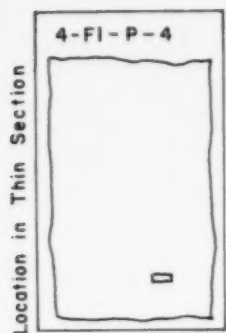


Figure 4 - Color Slides 4A,B



0.2 mm



Location in Thin Section

Figure 5 - Color Slides 5A,B